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LOS ANGELES AND LONG BEACH HARBORS MODEL ENHANCEMENT PROGRAM

MEASURED RESPONSE OF MOORED SHIPS TO LONG-PERIOD WAVES

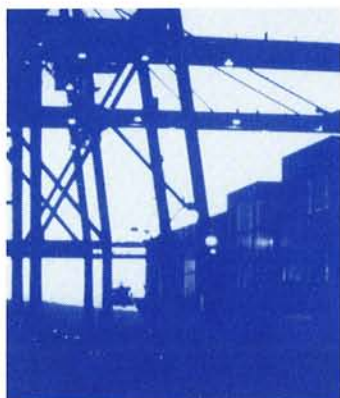
by

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DEPARTMENT OF THE ARMY

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September 1991

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for US Army Engineer District, Los Angeles
Los Angeles, California 90053-2325

Port of Los Angeles
San Pedro, California 90733-0151

and

Port of Long Beach
Long Beach, California 90801-0570



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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE September 1991		3. REPORT TYPE AND DATES COVERED Final report
4. TITLE AND SUBTITLE Los Angeles and Long Beach Harbors Model Enhancement Program, Measured Response of Moored Ships to Long-Period Waves			5. FUNDING NUMBERS	
6. AUTHOR(S) David D. McGehee				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) USAE Waterways Experiment Station Coastal Engineering Research Center 3909 Halls Ferry Road Vicksburg, MS 39180-6199			8. PERFORMING ORGANIZATION REPORT NUMBER Technical Report CERC-91-12	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) See reverse.			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A monitoring system was designed and operated at a coal terminal in Los Angeles Harbor and at a container terminal in Long Beach Harbor. The objective was to obtain the complete six degree-of-freedom response of vessels, as well as the mooring line and fender reactions, to measured long-period waves. A unique data set was collected on five separate ships. The data will be used to calibrate and verify a numerical, moored ship-motion model. The system design and sample data results are presented. Spectral analysis is used to illustrate relationships between waves and ship response.				
14. SUBJECT TERMS Harbor Monitoring Mooring			15. NUMBER OF PAGES 133	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED		18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED		19. SECURITY CLASSIFICATION OF ABSTRACT
20. LIMITATION OF ABSTRACT				

9. SPONSORING/MONITORING AGENCY NAMES AND ADDRESSES (Continued):

USAED, Los Angeles
Los Angeles, CA 90053-2325

Port of Los Angeles
San Pedro, CA 90733-0151

Port of Long Beach
Long Beach, CA 90801-0570

PREFACE

This report was prepared by the Coastal Engineering Research Center (CERC), US Army Engineer Waterways Experiment Station (WES), and is a product of the Los Angeles and Long Beach Harbors Model Enhancement (HME) Program. The HME Program has been conducted jointly by the Ports of Los Angeles and Long Beach (LA/LB); US Army Engineer District, Los Angeles (SPL); and WES. The purpose of the HME Program has been to provide state-of-the-art engineering tools to aid in port development. In response to the expansion of ocean-borne world commerce, the LA/LB are conducting planning studies for harbor development in coordination with SPL. Ports are a natural resource, and enhanced port capacity is vital to the Nation's economic well-being. In a feasibility study being conducted by SPL, the LA/LB are proposing a well-defined and necessary expansion to accommodate predicted needs in the near future. The US Army Corps of Engineers (CE) will be charged with the responsibility for providing deeper channels and determining effects of this construction on the local environment.

This report documents the Ship Motion Data Collection and Analysis subtask of the HME Program. Vessels were monitored in both harbors in February and March 1989 to provide validation data for numerical models. Mr. David D. McGehee of the Prototype Measurement and Analysis Branch (PMAB), Engineering Development Division (EDD), CERC, provided planning and management of the effort and conceptual design of the measurement system. Detailed design implementation of the data collection system was performed under contract to Evans-Hamilton, Inc. (EHI), of Houston, TX.

Integration of an intensive measurement study into the routine operations of one of the world's busiest ports could not be contemplated without the indulgence and assistance of scores of professionals that conduct the business of LA/LB. Mr. Daniel Zuliani of the National Lines Bureau coordinated the efforts by the members of International Longshoreman and Warehouseman Union, Local 13, who provided technical advice and willing hands that resulted in faultless installation of the tension monitoring hardware. Mr. Jim Holland of Kaiser International Corporation and Mr. Bruce Wargo of Stevedoring Services of America arranged access to the Kaiser Coal Terminal and the Pacific Container Terminal, respectively, as well as provided valuable technical data. Assistance was provided by the operations directors,

wharfingers, and shipping agents in both ports. In particular, respectful appreciation is extended to the captains of the monitored vessels, who carry the responsibility for their crew, vessel, and cargo, for permitting the participation of their ships in the study.

Mr. Robert C. Hamilton, President, EHI, prepared the comprehensive contractor's report that provided the basis for this technical report. An extraordinary level of effort was maintained by Mr. Nicholas G. Carter, Ronald W. Nance, Lloyd Stahl, Keith A. Kurrus, and Barbara Allen, EHI, during the construction, execution, and documentation phases to maintain schedules and budgets.

Other CERC personnel involved in the data collection were Messrs. William E. Grogg and William M. Kucharski, Equipment Specialists, and Mr. Jay Rosati, Hydraulic Engineer, all of PMAB. Data analysis was performed by Mr. James P. McKinney, PMAB, and Mr. Francis E. Sargent, Wave Processes Branch (WPB), Wave Dynamics Division (WDD), CERC, with the assistance of Ms. Deborah Shafer, PMAB. Mr. William C. Seabergh, WPB, served as principal investigator for the HME Program and coordinator for the various subtasks of the HME. The WPB personnel were under the direction of Mr. C. E. Chatham, Jr., Chief, WDD, and Mr. Dennis G. Markle, Chief, WPB. The PMAB personnel were under the direction of Mr. Thomas W. Richardson, Chief, EDD, and Mr. William L. Preslan, Chief, PMAB. This study was under the general supervision of Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC, and Dr. James R. Houston, Chief, CERC.

During the course of the study, liaison was maintained between WES, SPL, and LA/LB. Mr. Dan Muslin, followed by Mr. Angel P. Fuertes, was SPL point of contact. Mr. John Warwar and Ms. Lillian Kawasaki, Port of Los Angeles, and Mr. Michael Burke, Mr. Rich Weeks, and Dr. Geraldine Knatz, Port of Long Beach, were LA/LB points of contact and provided invaluable assistance.

COL Larry B. Fulton, EN, was Commander and Director of WES during the publication of this report. Dr. Robert W. Whalin was Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement can be converted to SI (metric) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
degrees (angle)	0.01745329	radians
feet	0.3048	metres
kips (mass)	453.5924	kilograms

LOS ANGELES AND LONG BEACH HARBORS MODEL ENHANCEMENT PROGRAM
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PART I: INTRODUCTION

Problem Statement

1. The Ports of Los Angeles and Long Beach (LA/LB), California, are conducting planning studies for a major expansion known as the 2020 Plan. This plan calls for reclamation of nearly 10 sq km of new landfill, construction of 38 new terminals, and the dredging or deepening of over 11 km of deep-draft channels. Systems of rail and highway connectors and intermodal container transfer facilities are included in the various configurations under evaluation.

2. The US Army Corps of Engineers (CE) is responsible for providing the deeper channels and determining the effects of this construction on the local environment. The development will affect the tidal circulation pattern in the harbor and the harbor resonance characteristics. To upgrade the CE's capability to estimate these effects based on state-of-the-art modeling technology, the US Army Engineer Waterways Experiment Station (WES) is executing the Los Angeles/Long Beach Harbors Model Enhancement (HME) Program.

3. Adequate circulation is necessary to ensure harbor flushing and acceptable water quality. Resonant oscillations caused by long-period waves (15 to 400 sec) entering the harbor may cause ship mooring and/or cargo handling problems. Long-period energy, or surge, has been observed in the LA/LB Harbors since at least the 1940's (Knapp and Vanoni 1945). The WES made model investigations of the Naval Base (Department of the Army (DOA) 1947a, 1947b), but studies of the entire harbor complex, with a long-term tidal circulation, harbor resonance, and ship-motion study, began in the 1970's. One year's worth of visual observations of moored ship response identified the East Channel in Los Angeles Harbor and Southeast Basin in Long Beach Harbor (Figure 1) as the most active areas (Durham et al. 1976).

4. By the 1980's, modeling and measurement techniques had advanced sufficiently to warrant upgrading these capabilities for application to the 2020 Plan. The HME Program was designed to obtain data for improving the

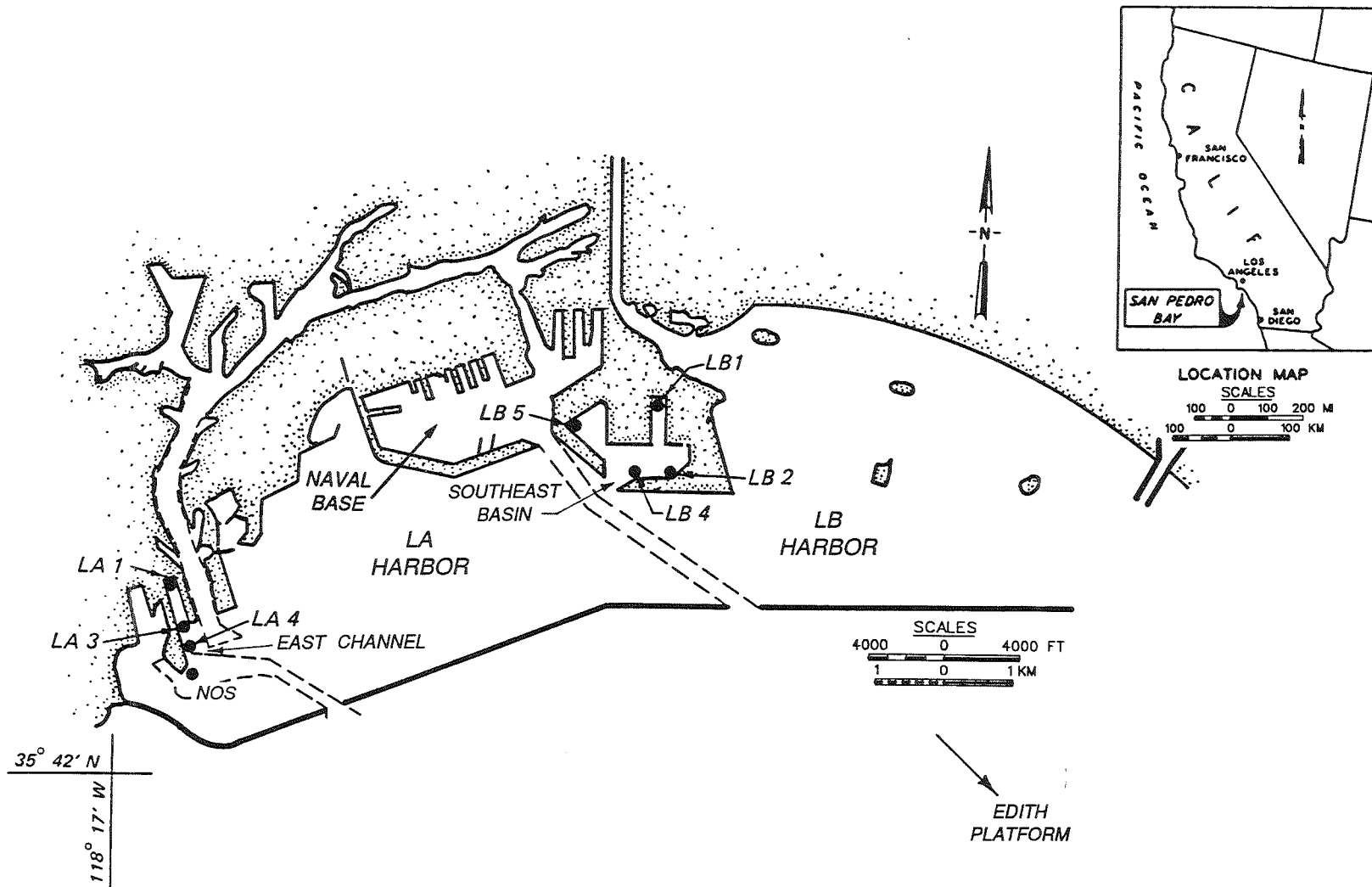


Figure 1. LA/LB Harbor Complex and positions of wave gages

evaluation of the harbors' response to tide, wind, and long-period wave forcing functions and to upgrade the capability of physical and numerical models to predict the effect of the planned expansion on circulation, water quality, harbor oscillations, and moored ship responses. The HME Program was performed by two WES laboratories: the Coastal Engineering Research Center (CERC) and the Environmental Laboratory (EL).

5. Tidal circulation was assessed using a state-of-the-art, three-dimensional (3-D) numerical hydrodynamic model (DOA 1990) validated with prototype tide and current measurements inside and outside the harbor complex (McGehee, McKinney, and Dickey 1989). In addition, an extensive network of wave and surge gages was established to measure the harbor resonance characteristics for comparison with a 3-D physical model. This network provided input conditions for the tidal circulation model as well as for the ship motion study described in this report.

6. The objective of the ship motion data collection effort was to obtain calibration and verification data sets for a numerical model of moored ship response to wind and waves. To validate the model, synchronous time series data were needed on the incident wave conditions outside the harbor, the mean water level, the harbor oscillation/response and wind conditions near the moored ship, the complete six degree-of-freedom ship response, and mooring line and dock/fender reactions. In addition, ship characteristics, mooring line geometry characteristics, and loading history were required.

7. Documentation of the effort is provided in two parts: (a) a technical report, which describes previous studies, provides the functional constraints the system was designed within, and summarizes the results, and (b) an unpublished contractor's report, which provides technical details on the design, construction and operation of the system and all of the resulting data.*

Background

8. The response to wave forces of ships adrift or underway has been extensively studied analytically, through physical and numerical models, and

* For additional information on the contractor's report, contact Mr. William C. Seaberg, CERC, WES, Vicksburg, MS 39180-6199.

through prototype measurements. With the advent of offshore loading terminals and floating drilling and production platforms, increased emphasis was placed on the response of vessels moored in the open ocean. In model studies of moored ships, the response was observed to be much larger for irregular waves than for regular waves of equivalent height. The reason for this larger response is that moored vessels respond to direct (first-order) excitation by the waves and to low-frequency wave-wave interactions, called slowly varying, or slow-drift forces, that occur in the same range as the vessels' natural modes of oscillation (Standing 1988).

9. In the early 1950's, the introduction of linear spectral methods advanced the theoretical ability to describe random waves (St. Denis and Pierson 1953). Extension of spectral analysis into the second-order effects allowed theoretical treatment of the slow-drift forces as the result of wave grouping in the incident wave train and diffractive interaction with the vessel (Newman 1975). However, relatively little investigation has been made into the reaction of vessels moored at a berth, subject to multiple mooring loads, fender reactions, wind loads, and hydrodynamic loads that include drift forces and harbor seiching as well as the higher frequency incident waves. Solutions have been formulated, with the simplifying assumptions of irrotational flow and small-amplitude, linear wave theory (Tekmarine 1988).

10. Laboratory validation of these models has been hampered by the problems of reproducing wave grouping and seiching in physical model tanks, and scaling the nonlinear stiffness of the mooring lines, though some techniques have been presented (Mansard and Pratte 1982). Reports of actual prototype scale measurements are even rarer. Some mooring line force data were reported for the US "Norton Sound" at Port Hueneme Harbor (O'Brien and Kuchenreuther 1958), but without simultaneous wave data.

11. A trawler (47-m length) was instrumented at Thorlakshofn Harbour, Iceland by the Icelandic Harbour Authority Research Section.* Five degrees of freedom were obtained (yaw being the exception) from a taut-wire measurement system affixed between the dock and the vessel. Inclinometers at each end of the wire, plus the wire's length, allowed calculation of ship motion data. An accelerometer-type buoy outside the harbor, a single pressure gage under the

* Icelandic Harbor Authority, 1987, "The Icelandic System for Measuring Ship Movements," unpublished report, Icelandic Harbour Authority Research Section.

ship, and a ship-mounted anemometer provided nondirectional incident wave conditions. Tension on four mooring lines was obtained from load cells. A similar approach, using three taut wires at bow, midships, and stern, was used to measure ship response at the Port of Acajutla, El Salvador (Stammers, Brockbank, and Wennick 1977).

12. Moes and Holroyd (1982) reported on a long-term installation of a monitoring system at Saldanha Bay, South Africa. An accelerometer buoy was used to measure short-period (up to 25-sec) incident waves. Long waves were measured by up to six pressure gages along the quay. A tide gage, anemometer, and current meter completed the input forcing function measurement. Mooring line loads were determined from strain gages placed on the sides of quick-release hooks on the quay. Eight pneumatic fenders were fitted with pressure transducers for calculation of fender forces. Ship position was determined photographically from a camera mounted along the quay axis. This position allowed determination of all but surge motions. Redundant position data were available from the output of a sonar docking device.

PART II: FUNCTIONAL CONSTRAINTS

13. Design of the measurement system was dictated by the type, duration and resolution of the data required by the model; the operating environment; and the overall HME Program schedule. The goal established by the HME Program was a minimum of 4-hr of data, each from at least two examples of two classes of vessels--bulk carriers and container ships. The locations selected were the Kaiser Coal Terminal in the East Channel, LA, and the Pacific Container Terminal in Southeast Basin, LB.

Model Properties

14. Ship response is modeled in a two-step process. A hydrodynamic model, HYDRO, calculates the resultant pressure field on the internal boundary, representing the hull, as the vector sum of the incident and scattered wave field and the radiated wave field due to unit displacements of the hull in six degrees-of-freedom.

15. The output of HYDRO is used to drive BERTH, which calculates the ship response to the wave and (steady) wind forces individually for each degree of freedom through the combined inertial, dampening, and reaction force transfer function. The output can be calibrated with added mass and wave dampening coefficients.

16. Output of BERTH is in the conventional form of pitch, roll, yaw, heave, surge, and sway referenced to a ship-board coordinate system with its origin at the center of gravity. Measured data are in the form of rotations and translations of an arbitrary point on the ship relative to a global coordinate system with a fixed origin. A coordinate transformation will be necessary to decouple the translation and rotation motions and allow direct comparison to the model output. Data presented in this report have not been transformed.

Operations

17. A measurement period from January to March 1989 was selected since the previous studies had shown a higher incidence of ship motion in winter. The goal of the monitoring plan was to obtain measurements of every ship that

berthed at the terminal where it was installed during this window. Monitoring activities could not interfere with or delay the routine mooring and loading of the vessels. Since two sites were selected for monitoring but only one could be monitored at a time, the decision on when an adequate database was collected at the first site could not wait on postprocessing. Consequently, all signal processing, data analysis, reduction, and display would be done in near real-time onsite. An uninterruptable power supply (UPS) was required to ensure data collection during power outages that might occur during storms.

Logistics

18. System portability was essential not only to allow transport to the harbors but to facilitate transfer between the two terminals. Breakdown, transport, and reinstallation time was limited to 5 days to minimize downtime. Both terminals had rail-mounted loading equipment that traversed the length of the ships during cargo transfer. These rails, and the continuous traffic of container or hopper trucks, prevented the placement of any large equipment near the vessel or the transit of any cables across the berth. Electronic equipment needed protection not only from the salt air but also from the persistent, and conductive, coal dust. The number and design of the bollards made the strain-gage approach used by Moes and Holroyd impractical. Regulations prevented nonunion personnel from handling mooring lines, so any in-line devices had to be deployable by longshoremen without extensive training.

PART III: SYSTEM DESIGN

19. The general approach was to minimize ship-mounted instrumentation; place computing and monitoring functions in a remote, though nearby, control trailer; and use radio telemetry to transmit signals. Two dock-side junction boxes provided battery power to, and received hard-wired signals from, the shipboard sensors and mooring line sensors; digitized the analog channels; and transmitted the data packet to the receiver in the trailer. Each box had a backup storage buffer to retain data in the event the telemetry link was lost. Other instruments, described below, sent radio and hard-wired data to the trailer for a total of 20 data and three video channels on seven telemetry paths (Figure 2).

Forcing Functions

20. An extensive array of wave gages was operated in and around the harbor complex under separate subtasks of the HME Program: Wave Data Acquisition and Wave Data Analysis. Incident, directional wave energy outside the harbor complex was obtained from a combined pressure sensor-electromagnetic current meter mounted on the "Edith" offshore production platform. Waves at seven locations within the harbor were measured using pressure transducers (Figure 1). Raw data were telemetered to a computer in LB Harbor for initial processing, then sent over phone lines to CERC for quality control, spectral analysis, and storage.

21. Wind data were obtained from a vortex shedding anemometer mounted on a tower above the control trailer. Tide data were available from a National Ocean Service (NOS) primary tidal station located in LA Harbor. Filtering of the pressure signals from the wave gages also provides mean water levels at each gage; excellent agreement with the NOS gage was obtained (McGehee, McKinney, and Dickey 1989).

Ship Motions

22. A remote-sensing approach to the ship's motion was desirable to avoid cargo traffic and expedite installation. However, the photographic technique was rejected because of limited resolution and the extensive

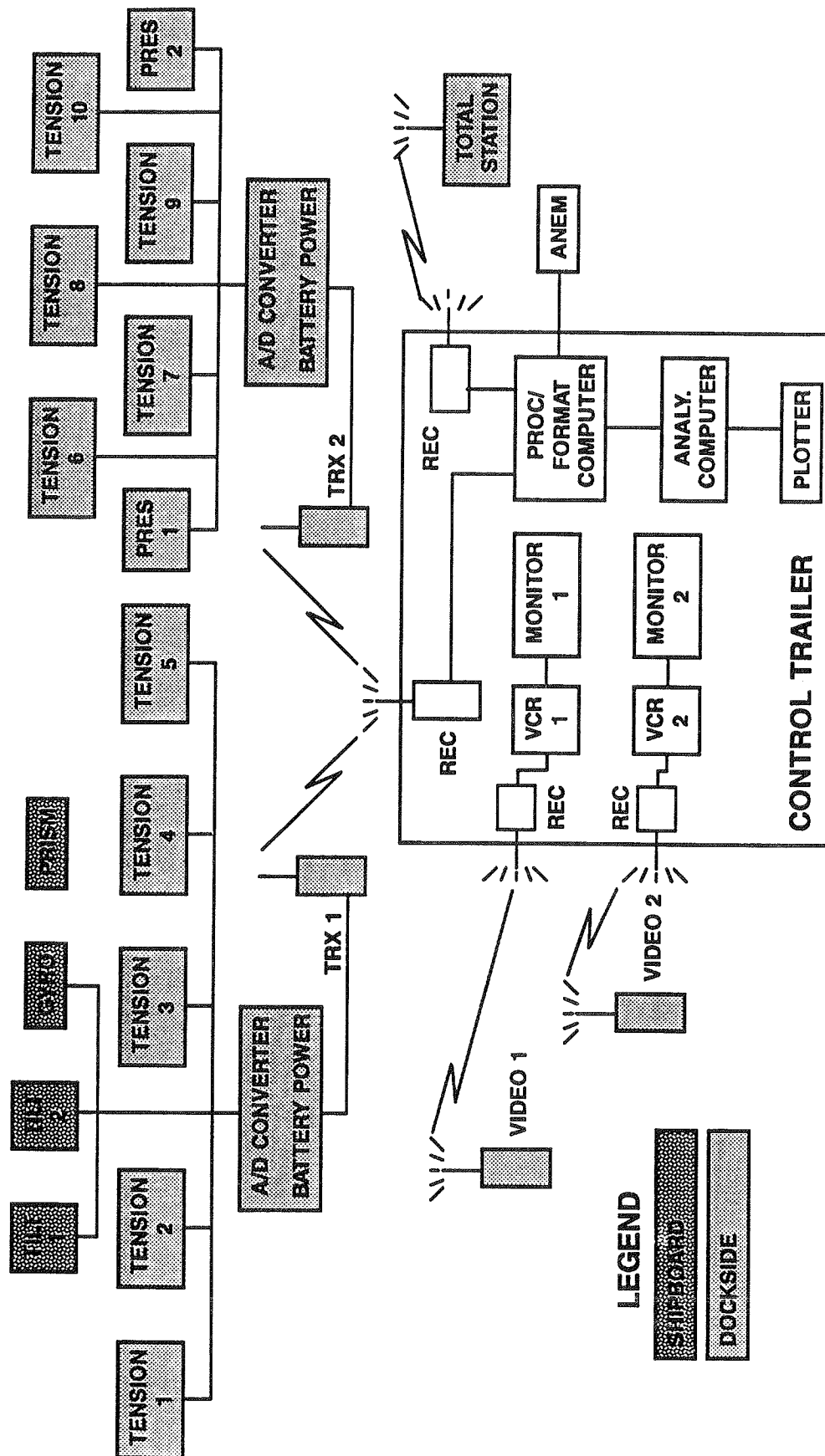


Figure 2. Schematic of system design and signal processing/data capture plan

postprocessing time required to reduce the images to engineering units. Instead, an auto-tracking total station was used to track a prism target placed on the ship's deck, providing translational measurements with survey-level precision. The unmanned total station was mounted dock-side on a self-propelled, scissors-lift elevating platform. It took one Hertz sample of range and vertical and horizontal angle to the target and transmitted the data either by hard-wire or by FM radio link. A miniature black-and-white video camera could be attached to the instrument's optical sight to provide remote verification that the target was being tracked.

23. The requirement to place the prism on the vessel opened the door for other ship-board instrumentation. A battery-powered module containing two orthogonal tilt sensors and a gyrocompass provided rotational motions. The prism was mounted above this module, which was hard-wired to one of the junction boxes.

24. Video imagery from two dock-mounted cameras (bow and stern) was a low-cost addition that served three purposes: a redundant, though less accurate, motion measurement system in the event of failure of the primary system; monitoring of the ship and instrumentation from the control trailer; and, by postprocessing the images, excellent visualization and display of the general characteristics of the ship's response. Each camera was on an elevating platform and used its own microwave telemetry channel to the video monitors and recorders in the control trailer.

Reaction Forces

25. Waterproof strain-gage type load cells were placed in-line between the ship's mooring lines and the bollards (Figure 3). While the other measurement activities represented an inconvenience, at worst, it was anticipated that any device placed between the dock and the ship would be a topic of considerable concern to the vessel captain. Therefore, the tension link hardware was designed to avoid even the appearance of a "weak link" in the mooring system. The waterproof cells are constructed of 13-cm-diam stainless steel and are rated to measure up to 45,000 kg, with a 300-percent overload capacity without failure. These were secured to the bollard with a wire rope sling and to the eye in the ship's mooring line with 32,000-kg load shackles. Five tension links were hard-wired to each junction box.

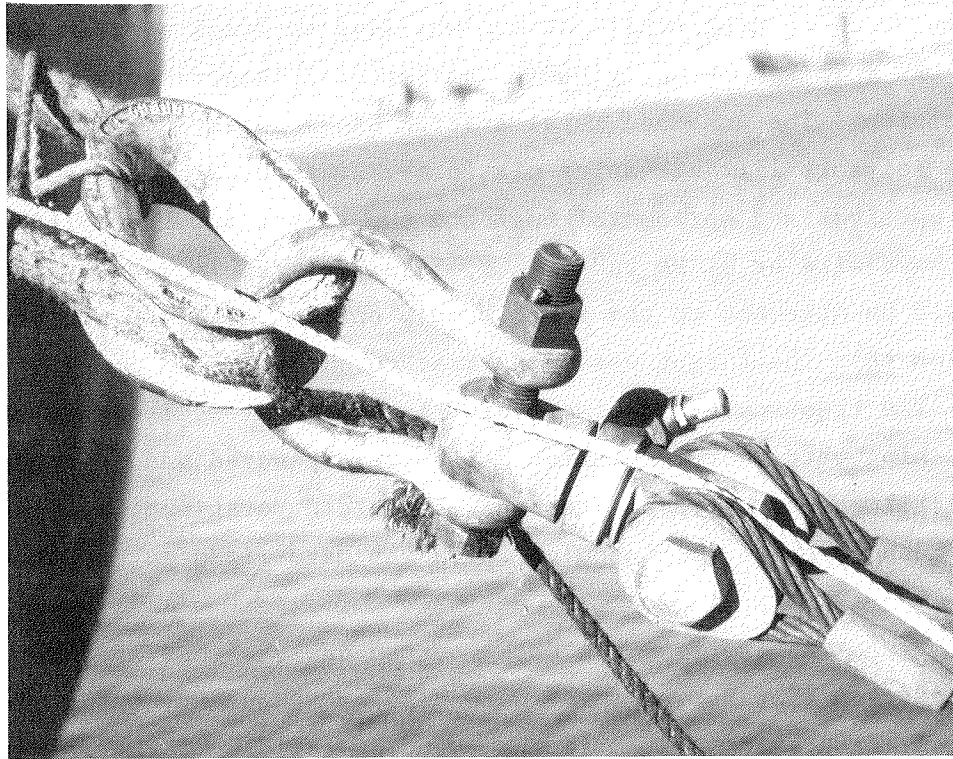


Figure 3. Tension link mounted in-line between ship and bollard

26. The presence of cylindrical pneumatic fenders at the coal terminal presented the opportunity to easily obtain fender reactions. Pressure transducers were fitted to the inflation valves of two of the fenders (bow and stern) and wired to a junction box. Data from the fender manufacturer allowed conversion of the pressure to force. Wooden fender piles at the container terminal were not suited for instrumenting. After initial deflection, the piles make contact with the pier and can be considered as rigid bodies in the model.

Signal Processing

27. The control van contained the five telemetry receivers, two primary and a backup video recorders with monitors, a black-and-white monitor for the total station camera, two 386 personal computers, two laser printers, the UPS, and peripheral test equipment. The receivers converted all raw data channels to standard RS-232 serial data streams for input into the first computer.

28. The first computer converted the signals into engineering units, performed transformation of the total station's range-angle-angle output into dock-referenced x, y, z coordinates, and stored all raw and converted data on a removable hard disk. The second computer synchronized and merged the reduced data channels into a 1-hr time series file and performed tabular and graphic displays. A second hard disk stored the merged files. Ten custom programs were required to manage the data collection, reduction, display, and storage. Complete specifications for all sensors, circuit diagrams for all electronics, and code for all software developed as a result of this study are contained in the contractor's report.

PART IV: SYSTEM OPERATION

29. At each terminal, the control van, the total station, and video platforms were placed at sites that provided the necessary line-of-sight without impeding loading operations. The positions of these platforms and the dock configuration, including the instrumented bollards and fenders, were surveyed using the total station.

30. Operations began by contacting the ship's captain, usually by sending out a CERC representative with the pilot, to explain the operation and obtain permission to instrument the vessel. As the ship approached the berth, longshoremen attached the tension links as they secured the ship. With mooring complete, the ship-board module was placed in view of the total station and aligned with the ship's axis.

31. As the automated data logging proceeded, additional types of data were obtained. The geometric layout of the shipboard module, the mooring lines, and deck gear were video recorded and measured. The ship's heading and pitch and roll angles were taken from the bridge for comparison purposes. Mooring line length, size, material, construction, and condition were recorded. Ship documents, including deck arrangement, load/displacement tables, trim and stability curves, were copied if they were made available. Periodically, draft was noted from the ship's hull. The time-dependent loading history was available from the Kaiser Coal Terminal when the traversing, conveyor-fed hopper was used. At the container terminal, the weight and position of each container was available, but the actual time of placement or removal was not routinely recorded. All the above information is contained in the contractor's report.

PART V: RESULTS

32. Three bulk carriers and two container ships were monitored between 15 February and 28 March 1989. Displacements ranged from 9,571 to 70,000 dead weight tons (DWT). Data recovery was not always continuous from ship arrival to departure for a variety of reasons. The automated system itself performed quite well. Instrumentation problems were primarily due to power distribution losses that caused periodic spikes in the transmitted signal that were not initially noticed in the graphic output. Poor positioning of the total station allowed it to be "blinded" by the rising sun for several hours on the first setup. Some software problems were discovered and corrected the first day of operation. Most data loss, however, could be attributed to procedural and communication failures.

33. Delays were experienced with instrument installation for all but one of the vessels as owners, captains, port, and government representatives decided access and liability issues. Consensus on wording of waivers and permits varied from vessel to vessel. In some cases, language barriers or privacy issues prevented the acquisition of ship documents. Poor communications also affected the proper tensioning of mooring lines. The availability of only 10 load cells was recognized as a constraint early in the plan formulation, but was considered acceptable if each bollard had at least one instrumented line and if multiple lines to the same bollard were similarly tensioned. The crew of some vessels, however, would add or readjust lines after berthing, often leaving the instrumented line slack.

34. One parameter that affected ship displacement and trim but was not monitored was the ballasting and fueling operations performed by the crew. The amount and position of fuel stores could be obtained from ship records, but ballast was not documented. The only vessel that was known to adjust ballast at the dock was the "Coral."

35. In spite of these problems, the HME Program's target objective was surpassed. Table 1 lists the types of data and length of successful measurement periods for each vessel. The complete 8.2 megabyte data set is stored as an ASCII file on magnetic media. Every vessel that docked at each terminal during the study period was monitored. Twenty-two subsets of one-half hour length representing a variety of loading conditions were selected for the model calibration/verification effort (Plates 1-95). This represents the most

Table 1

Channel	Start Anagel Progress 049-12-00	Stop Anagel Progress 049-16-45	Start Anagel Progress 050-09-20	Stop Anagel Progress 050-17-44	Start Permas Arang 066-10-29	Stop Permas Arang 066-14-34	Start Permas Arang 066-14-45	Stop Permas Arang 066-18-3
1 Tension Link 1								
2 Tension Link 2								
3 Tension Link 3								
4 Tension Link 4								
5 Tension Link 5								
6 Blank 1								
7 Blank 2								
8 Bumper Pressure 1								
9 Tension Link 6								
10 Tension Link 7								
11 Tension Link 8								
12 Tension Link 9								
13 Tension Link 10								
14 Roll								
15 Pitch								
16 Bumper Pressure 2								
17 Gyro Heading								
18 Geodimeter X								
19 Geodimeter Y								
20 Geodimeter Z								

Wind Speed

Wind Direction

Time Format Ex: 049-12-00

049 = Julian Day, 12 = Hour, 00 = Minute

(Continued)

Table 1 (Concluded)

Channel	Start	Stop	Coral	Start	Stop	Hui He	Start	Stop	Hui He	Start	Stop	Ta He	Start	Stop
1 Tension Link 1	068-09-55	068-13-36		080-18-52	081-02-48		081-11-49	081-16-49		086-15-46	087-00-0			
2 Tension Link 2														
3 Tension Link 3														
4 Tension Link 4														
5 Tension Link 5														
6 Blank 1														
7 Blank 2														
8 Bumper Pressure 1														
9 Tension Link 6														
10 Tension Link 7														
11 Tension Link 8														
12 Tension Link 9														
13 Tension Link 10														
14 Roll														
15 Pitch														
16 Bumper Pressure 2														
17 Gyro Heading														
18 Geodimeter X														
19 Geodimeter Y														
20 Geodimeter Z														
Wind Speed	068-09-55	068-09-16		080-18-52	081-02-48		081-11-49	081-16-49		086-15-46	087-00-0		086-13-50	087-10
Wind Direction	068-09-55	068-09-16		080-18-52	081-02-48		081-11-49	081-16-49		086-15-46	087-00-0		086-13-50	087-10

Time Format Ex: 049-12-00 049 = Julian Day, 12 = Hour, 00 = Minute

complete data set available in terms of the type and amount of data collected and the number of ships monitored.

PART VI: DISCUSSION

36. The monitoring period was unusually calm, compared with previous winters. Figure 4 shows the time series of the total incident energy (8 to 2,048 sec) and the low-frequency portion (25.6 to 2,048 sec) in cm^2 from the directional gage on platform "Edith" outside the harbor for March 1989. These values represent very low waves that resulted in little energy entering the harbor, and thus, small ship motions and low mooring forces.

37. Maximum measured translations were on the order of 3 m in sway and 2 m in surge, in the case of the "Coral," but this was attributed to excessive slack in the mooring lines, evidenced by tension link signals that were only intermittently nonzero. An 8-deg list is also evident that may have exaggerated normal response (Plates 20-25).

38. A portion of the time series from the "Hui He" on March 22 is presented in Figures 5 and 6. (In the ensuing discussion, X, Y, and Z signals from Figure 6 are referred to as surge, sway, and heave, respectively, though they have not been transformed to ship-referenced vectors.) The mooring line geometry is illustrated in Figure 7 by tension link number. One of the bow lines, tension link 1 (TL1), can be seen responding to the surge oscillations. The other bow line (TL2) and an aft breast line (TL8) are nearly slack. A near-slack stern line (TL9) shows additional response to the somewhat slower sway oscillations, because of a steep approach angle. A higher frequency harmonic (near 14 sec) is evident in all of the tension links and in the sway signal, but it is actually due to the roll. The coupling of the sway and roll signals is an artifact of using the untransformed, global coordinate system.

39. Just before 1500 hr, all of the lines were tightened. The reduction in surge and sway is dramatic. Roll response is also reduced, but not eliminated. The low amplitude heave response (on the order of 5 cm) seems completely unaffected. The 14-sec "strumming" in the mooring lines is enhanced, as kinetic energy is transferred to elastic energy in a higher harmonic. Attention is brought to this obvious effect of snugging up lines to illustrate a simple quality check of the data.

40. Spectral analysis of the time series is another tool for investigating relationships between the signals. A 34-min segment of this record, before the lines were tightened, was transformed into the frequency domain. Figures 8 and 9 are plots of the normalized energy of six selected tension

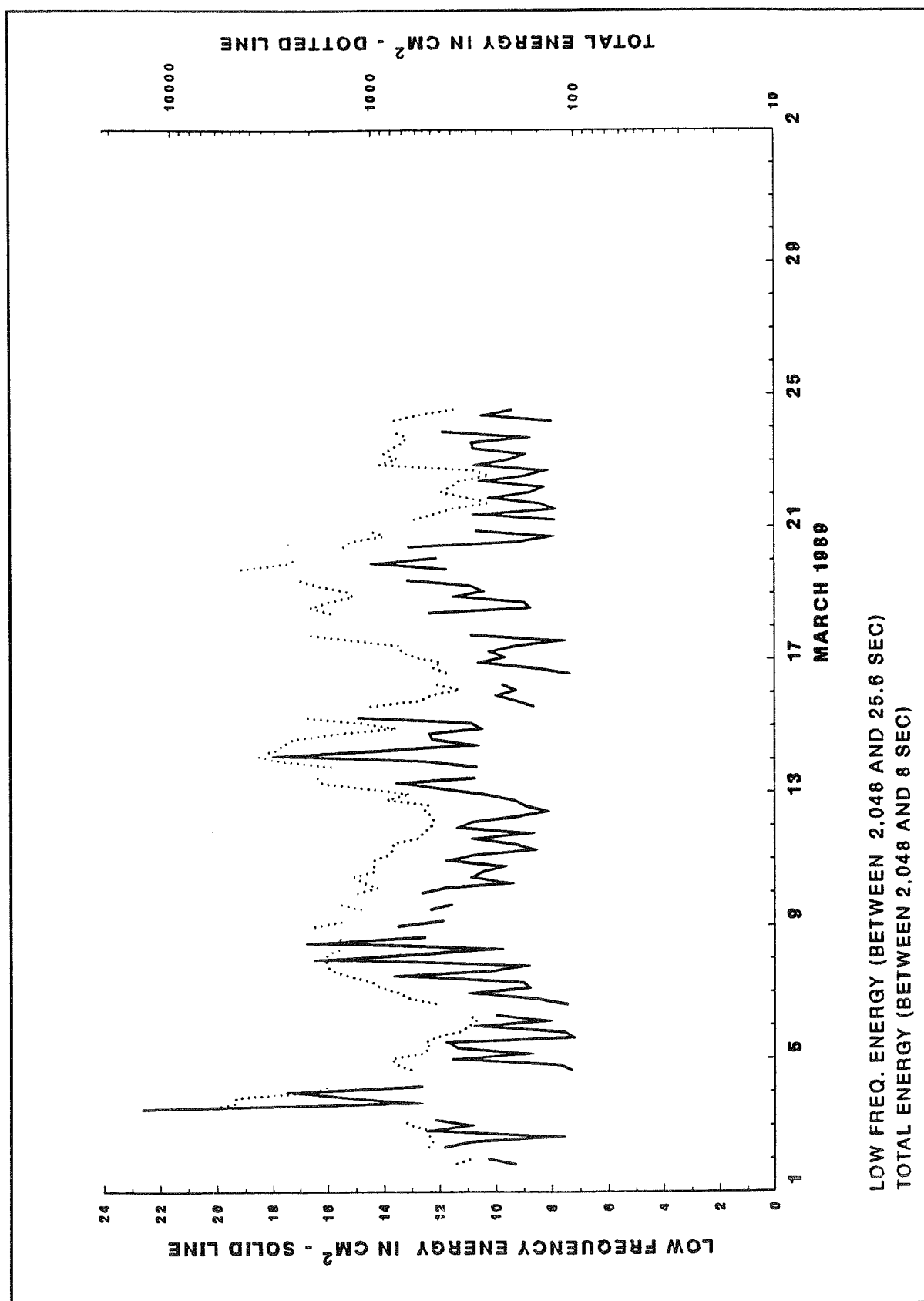


Figure 4. Time series of incident energy from platform "Edith"

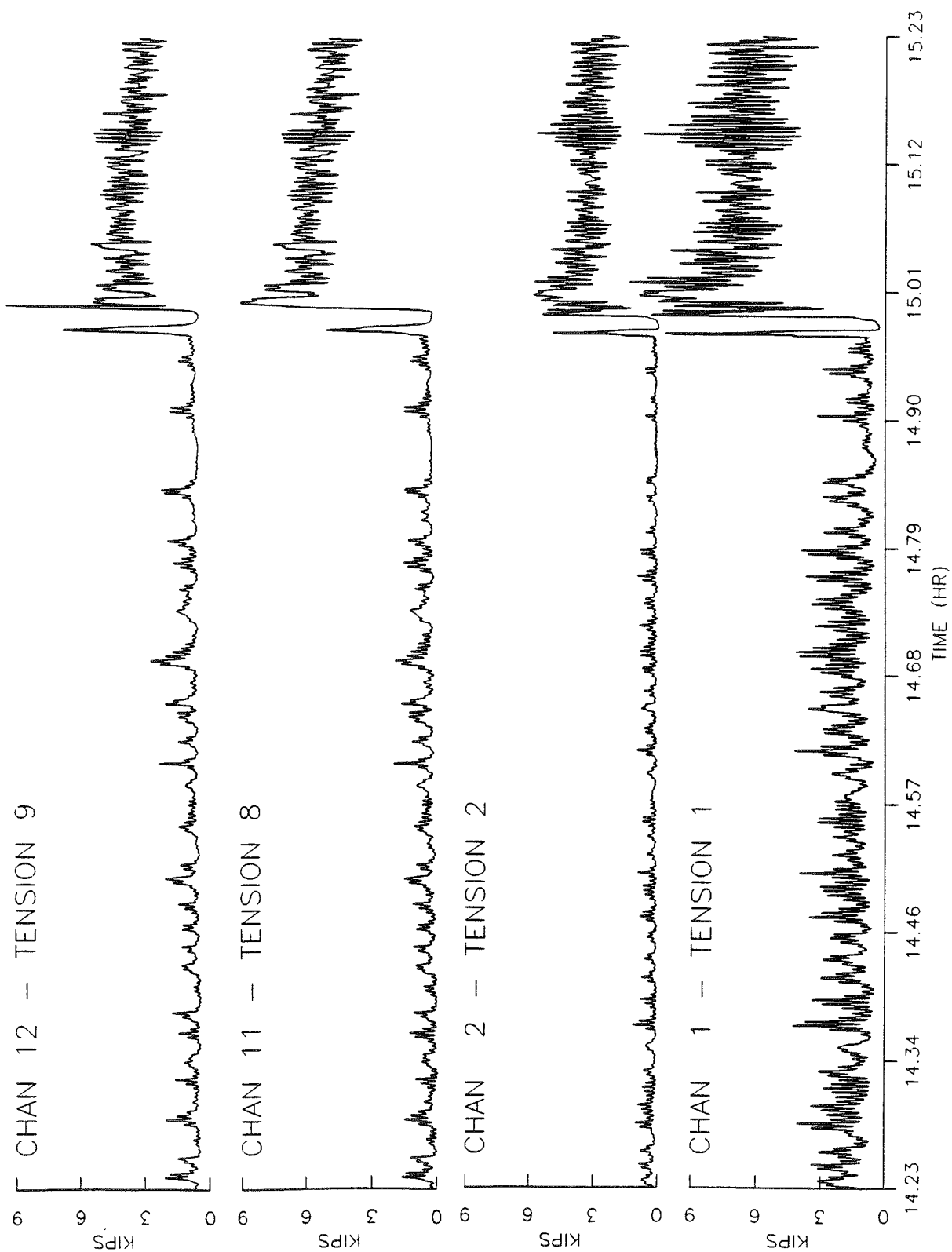


Figure 5. Tension link reaction time series from "Hui He," 22 March 1989

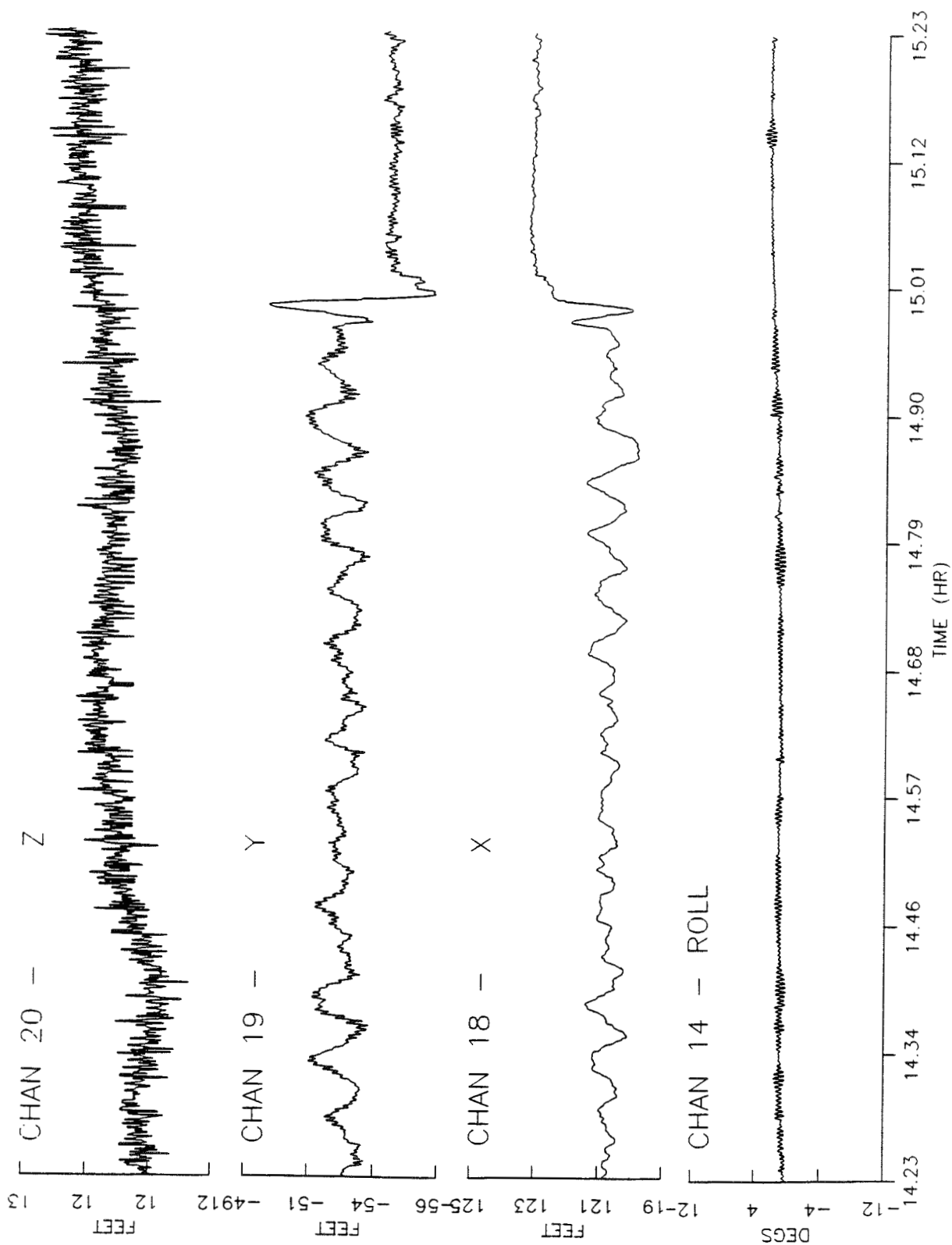


Figure 6. Ship motion time series from "Hui He," 22 March 1989

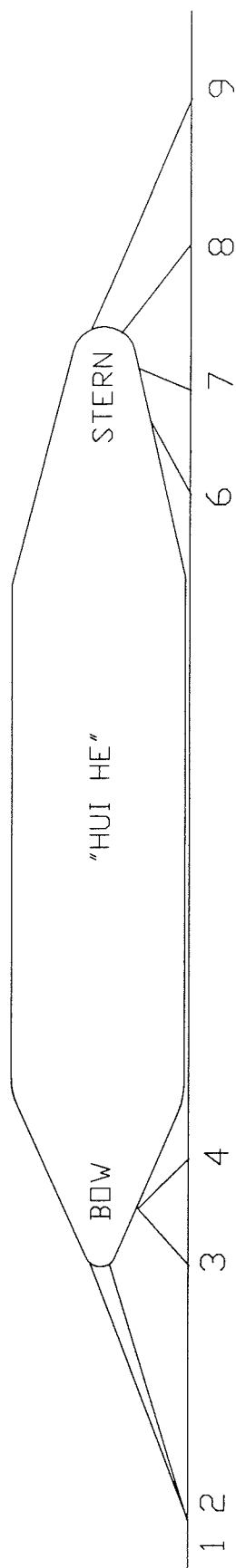


Figure 7. Mooring line geometry for "Hui He," 22 March 1989

LOW FREQUENCY ENERGY > 25 SECONDS

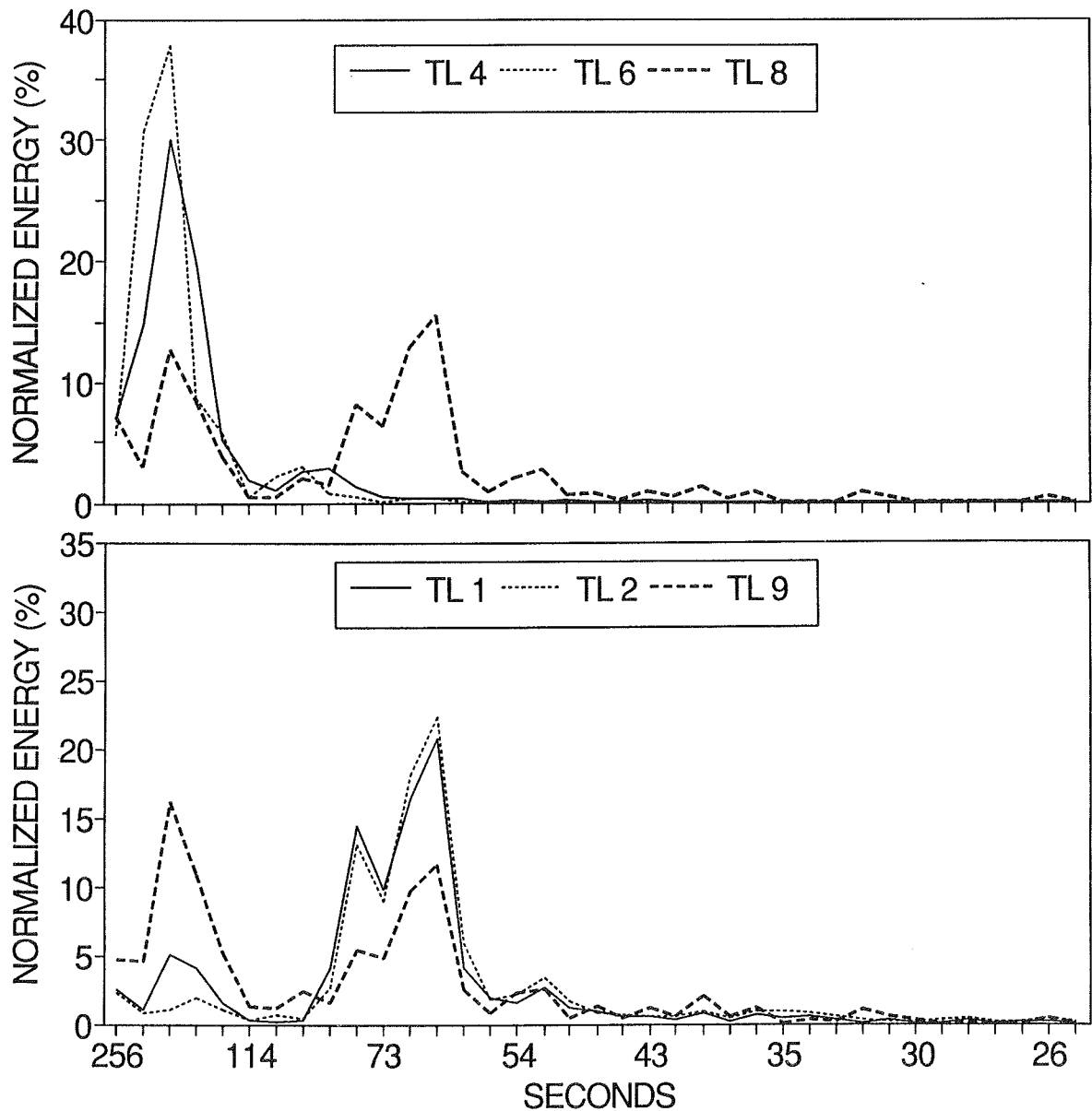


Figure 8. Energy spectra of tension links for "Hui He,"
22 March 1989

LOW FREQUENCY ENERGY > 25 SECONDS

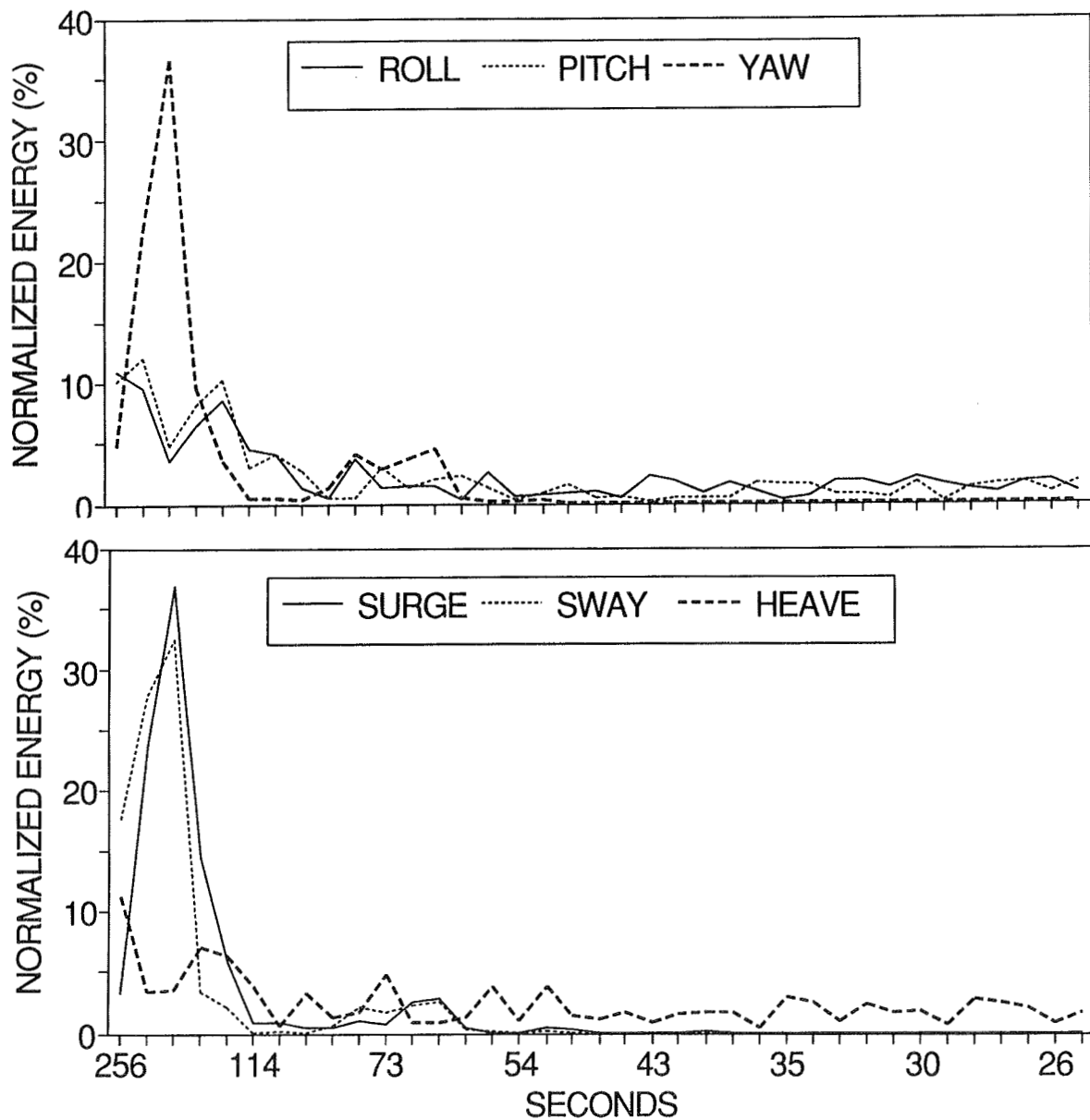


Figure 9. Energy spectra of ship motions of "Hui He,"
22 March 1989

links and the six vessel motions as a function of frequency. Each channel is normalized independently; i.e., a value of 20 percent for surge means that 20 percent of the surge energy measured is found at that frequency, but does not imply this motion has the same amplitude as a 20-percent value for heave. Only the low-frequency energy, longer than 25 sec, is included.

41. The peaks of the energy spectrum for surge, sway, and yaw are around 170 sec, as are those for the two spring lines, TL4 and TL6. Pitch and roll show similar double-humps in the 100- to 300-sec range. Secondary humps between 60 and 80 sec in all six degrees of freedom appear to be responsible for the majority of the low-frequency reactions in bow lines, TL1 and TL2. TL8 and TL9 are stern lines, but are attached outboard of the ship's center line, so they divide these two modes more or less equally. Differences in the modes of oscillation of the lines is also dependent upon their tension. TL1, the tightest, has the strongest response beyond the range of this plot, at the 16-sec roll period described in the next paragraph. The looser bow line, TL2, has its peak response at 64 sec. The heave signal shows little pattern or correlation with other signals because the very low amplitude of the motion is masked by the background "white" noise in the system.

42. To identify the input wave energy associated with these motions, it is necessary to extend the analysis beyond the long-wave domain into higher frequencies. Figure 10 includes energy out to 8-sec periods for the motions and corresponding spectra for LB2 and LB4, the two wave gages on either side of the ship. Forcing energy for the 14-sec roll, pitch, and yaw evident in the time series is apparent in the narrow peaked wave spectra.

43. A much smaller hump in the wave spectra near 64 sec produces a noticeable effect in surge, sway, and yaw. The predominant mode of oscillation for these three motions, representing one third of the total energy, is at 170 sec. However, only about 1 percent of the wave energy can be accounted for in this range. This illustrates the nonlinearity of the slow drift forces described earlier, and the importance of accurately predicting ship response to them.

44. No loading problems were reported during the study at the coal terminal. At the container terminal, the "Ta He" spent 2 days in port instead of the scheduled 1 due to motion-related delays in transferring containers. Maximum sway was on the order of a meter, but the long-period sway should not have presented an impediment to crane operators. Maximum roll was

TOTAL ENERGY > 8 SECONDS

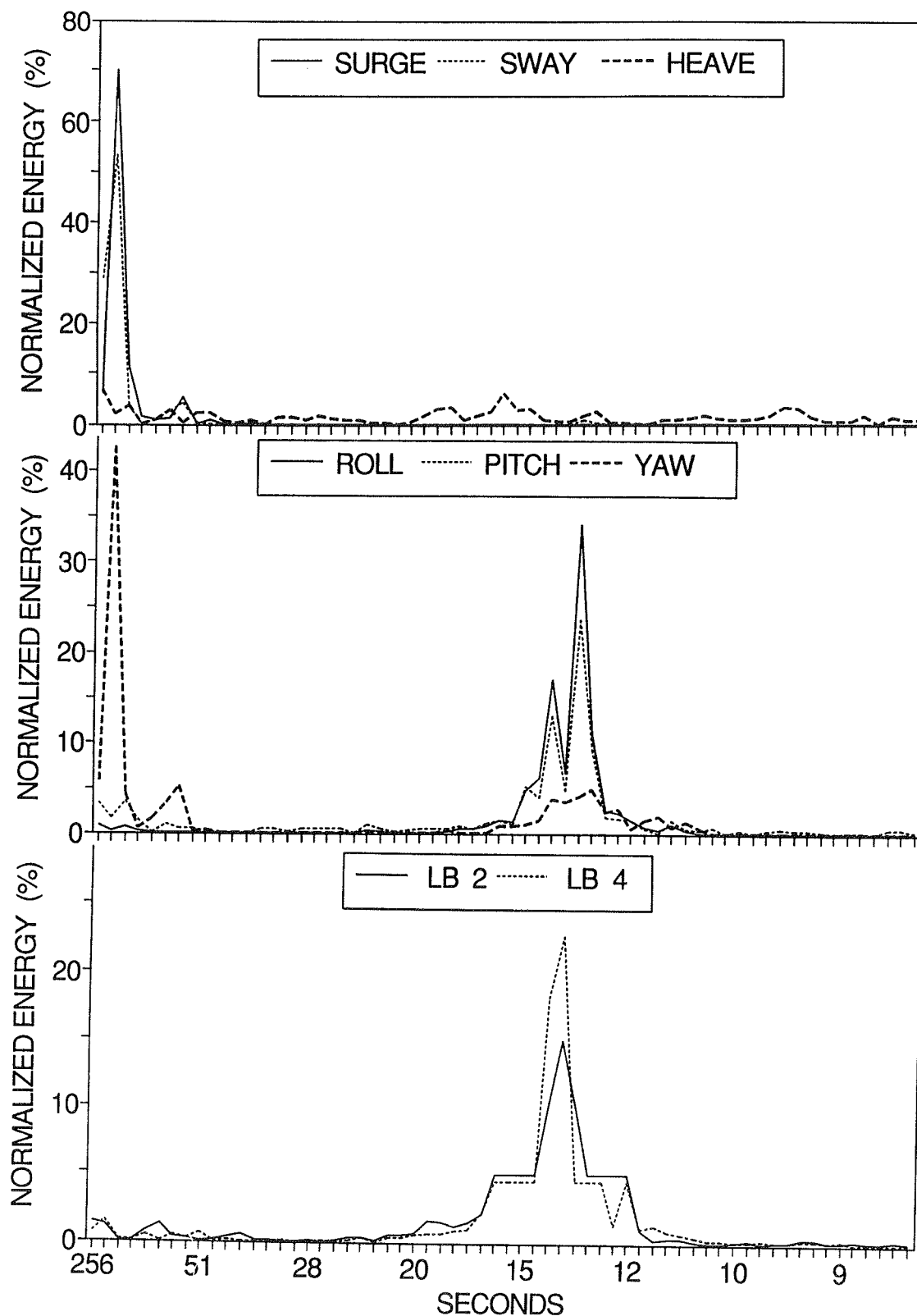


Figure 10. Energy spectra of waves in basin and resulting motions of "Hui He," 22 March 1989

approximately 2 deg,* which would produce motions of nearly a meter, if the upper layer of containers was on the order of 20 m above the center of gravity. Roll frequency, however, was much higher, resulting in higher velocity motions. The difficulty this 12- to 14-sec, 1-m amplitude oscillation caused the operators is quite evident from the video recording, particularly when viewed at higher speeds.

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 5.

PART VII: CONCLUSIONS

45. An effective strategy was developed to allow measurement of the six-degree-of-freedom response of moored ships, as well as mooring line and fender reactions, to low-frequency wave energy. Five ships were monitored under typical loading conditions without interfering with terminal operations. This represents the most complete data set of this type reported. Though conditions during the study were moderate, sufficient vessel motion occurred in one case to double the expected loading time. Capture of more extreme conditions, as for any episodic event, would require a long-term commitment to either a permanent installation at one site or a highly portable, rapid-deployment system in a standby mode.

46. Measurements verified and quantified some expected results. Slackening lines increases, and tightening lines reduces ship motions. Tighter lines react more strongly to higher frequency motions. Maximum vessel excursions are typically due to surge, sway, and roll; heave shows the lowest amplitudes. Transferring containers, due to the height of the cargo above the ship's center of gravity and the operational limits of the container cranes, is sensitive to even low-amplitude wave energy.

47. The peak of the measured spectra for the measurement interval in the Southeast Basin was typically around 14 sec, which is very near the resonant roll mode of the two container ships measured. A lower harmonic near 64 sec excites surge and sway, but these two modes, together with yaw, are dominated by slow drift at periods near 170 sec.

48. While technical problems caused some data loss, the major obstacles to monitoring ships of opportunity were legal and administrative. Any future efforts would be enhanced by more advance contact with the vessel owners and masters, though uncertain schedules and communication barriers remain problems. Given time, dissemination of the goals and benefits of such research efforts to the shipping community at large may remove some obstacles. Coordination and sanction by a recognized authority, such as the Permanent International Association of Navigation Congresses, would encourage involvement.

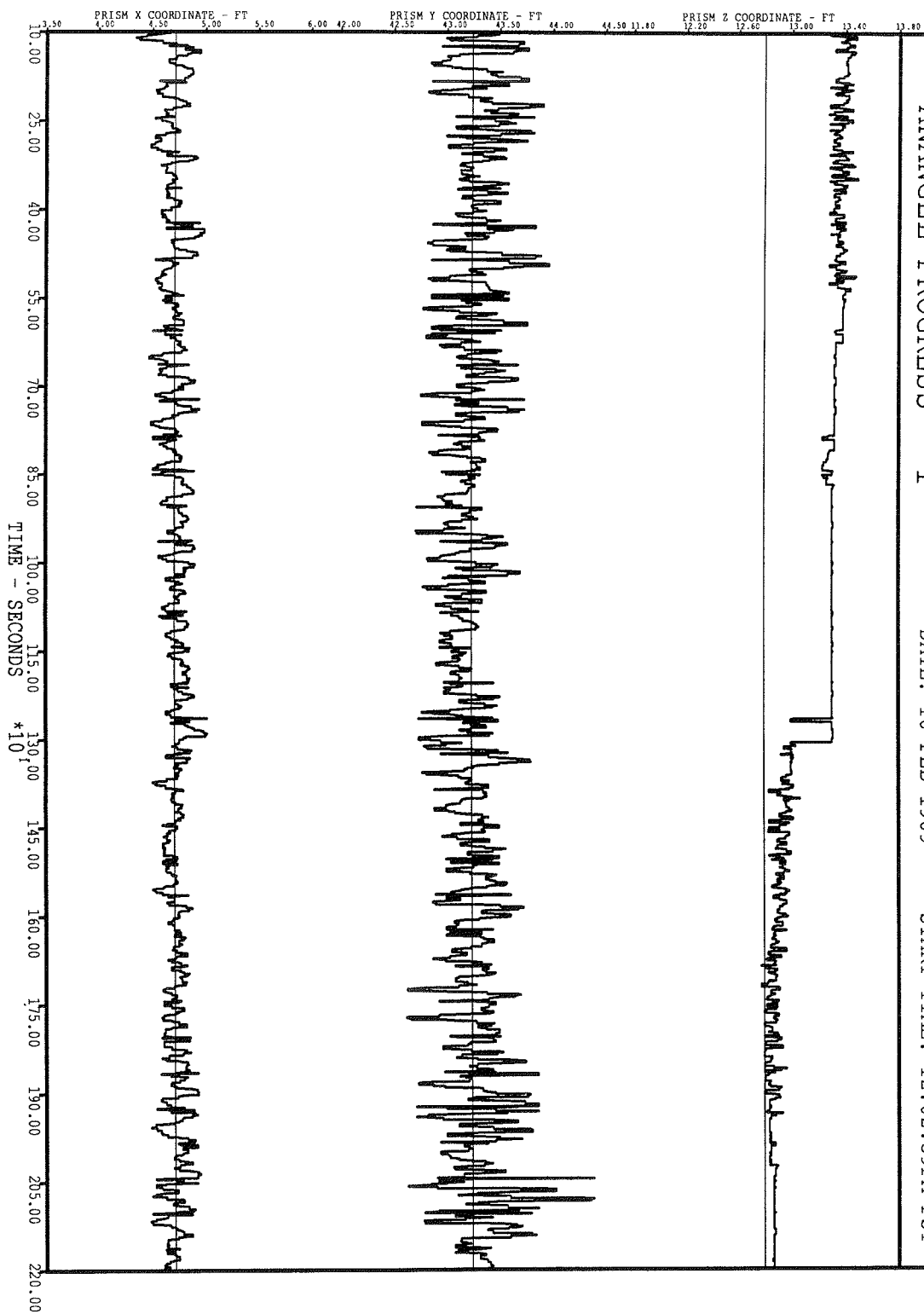
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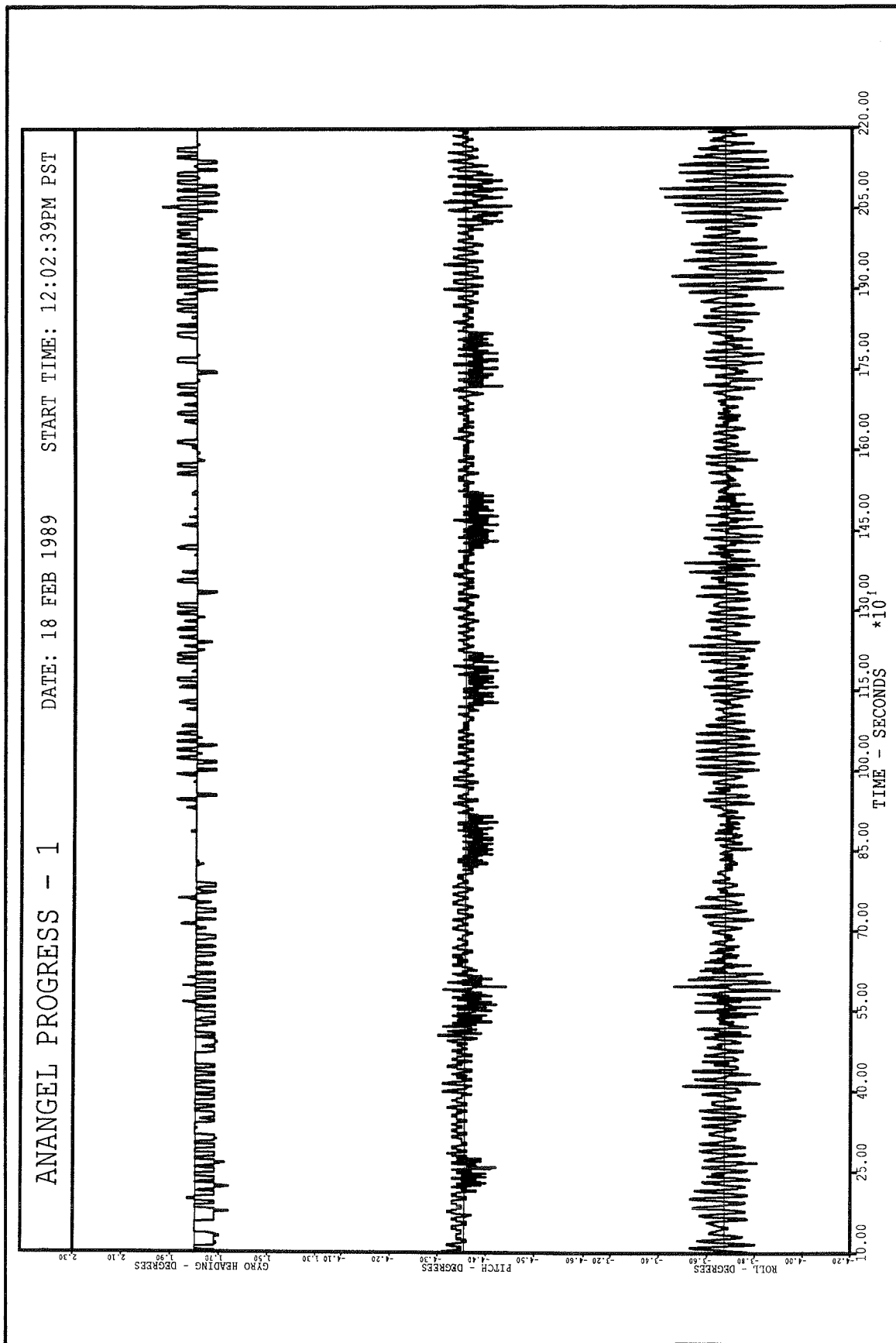
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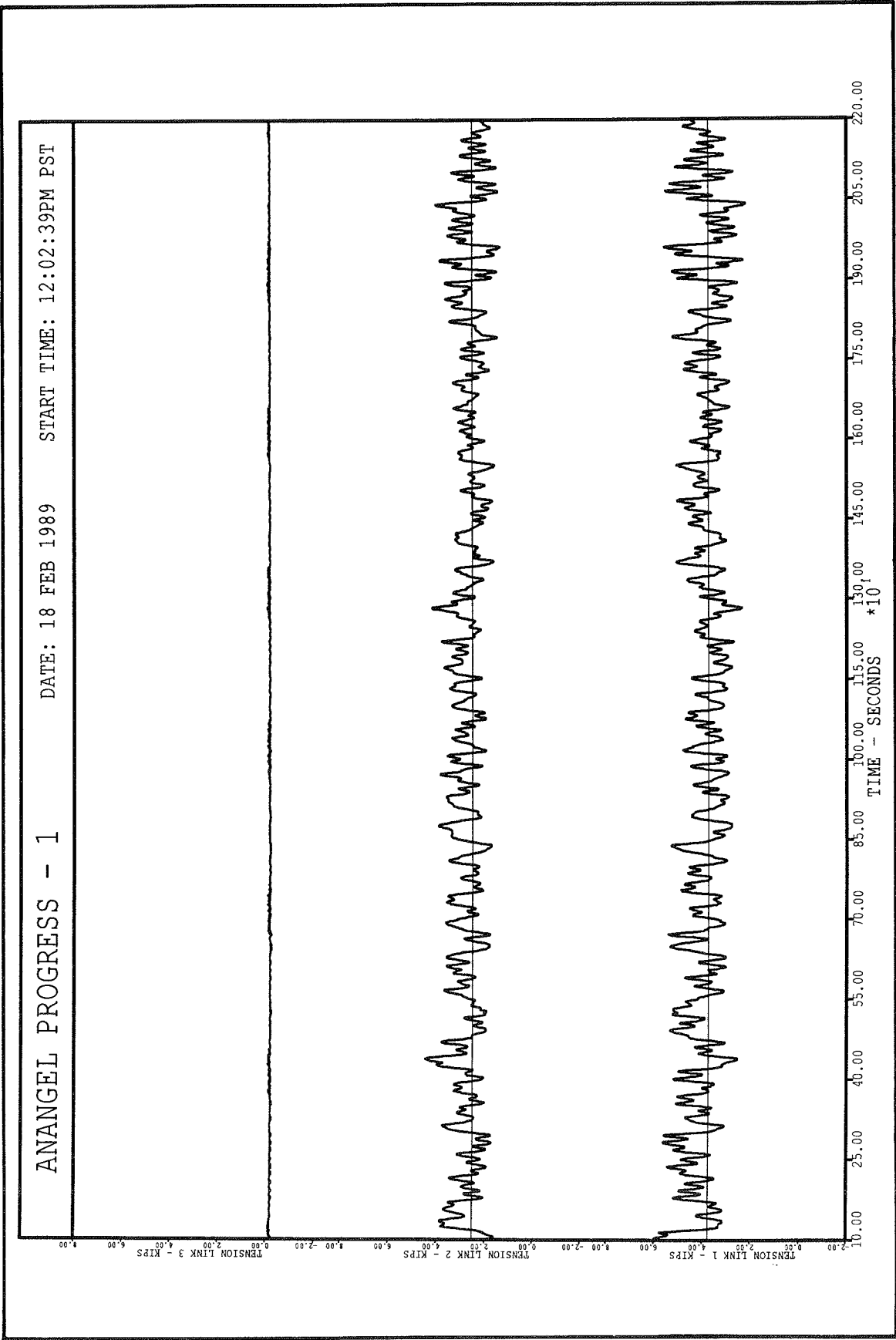


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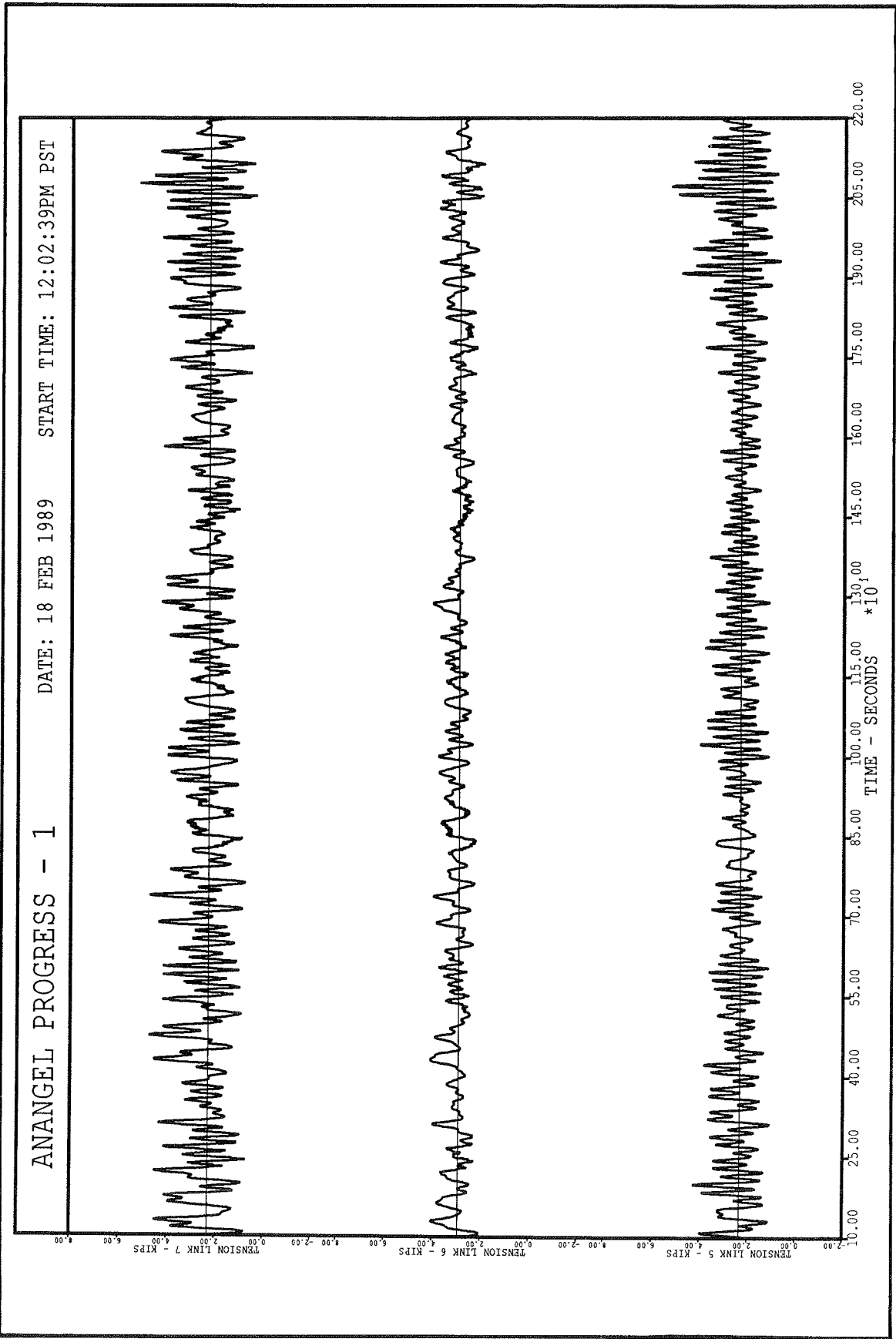
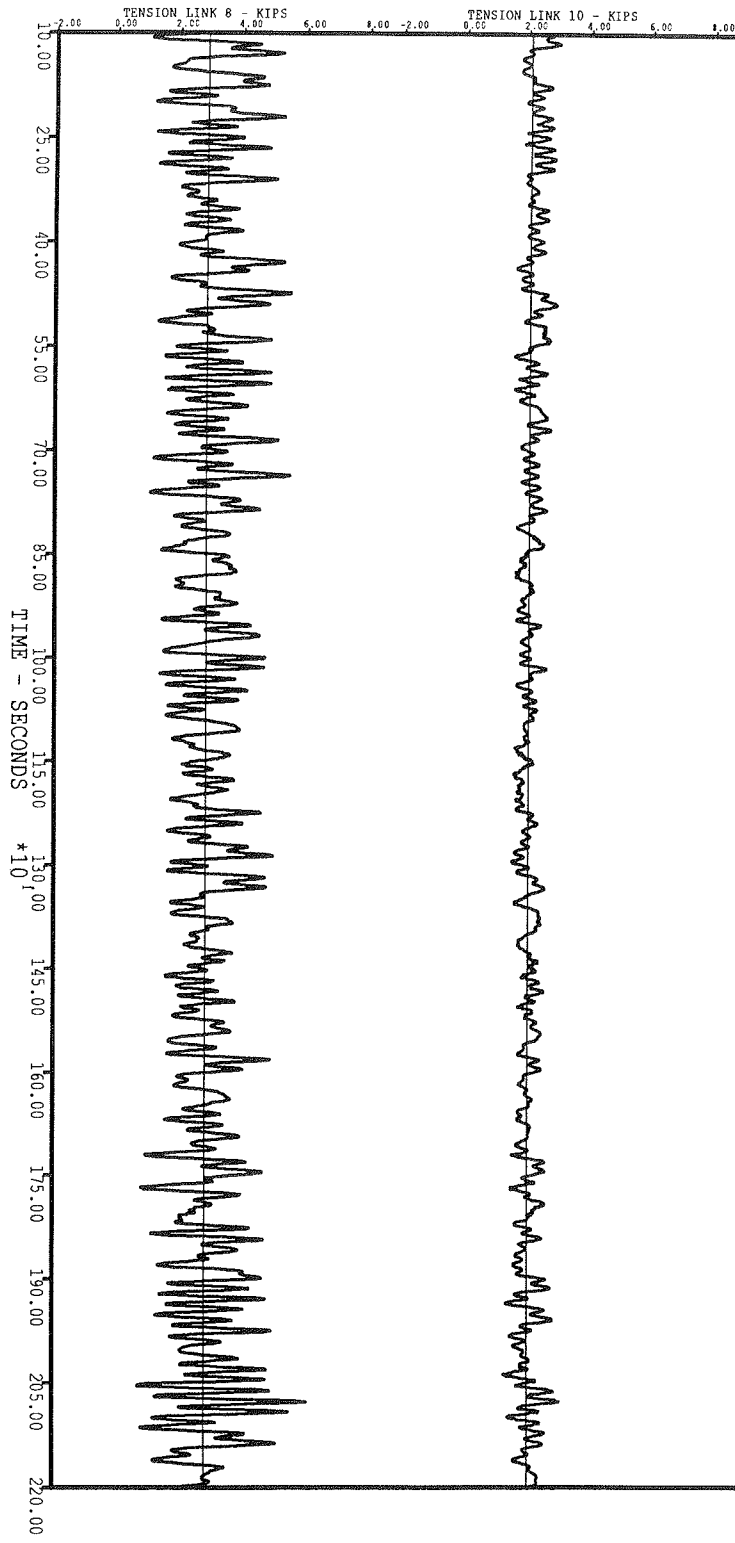


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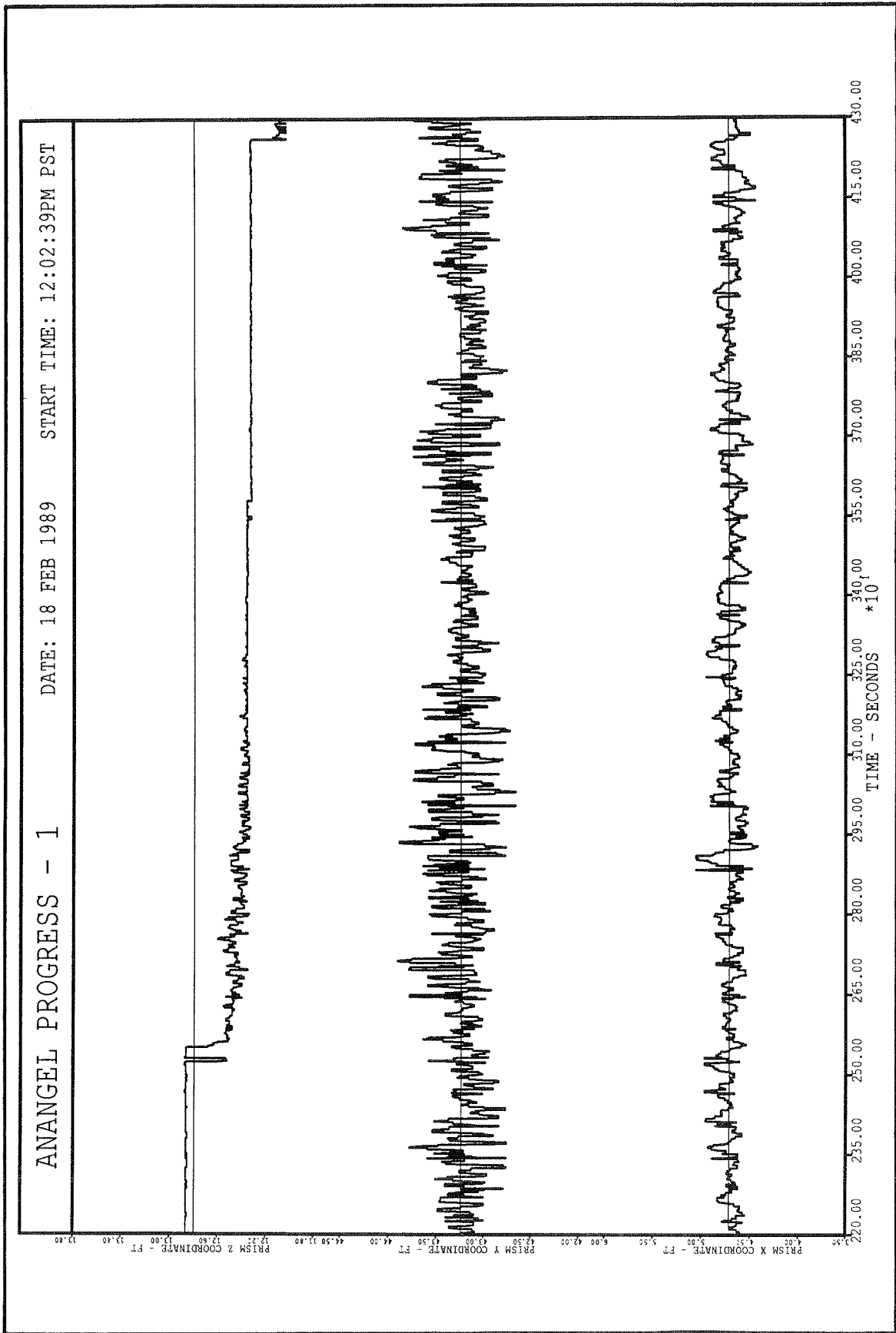
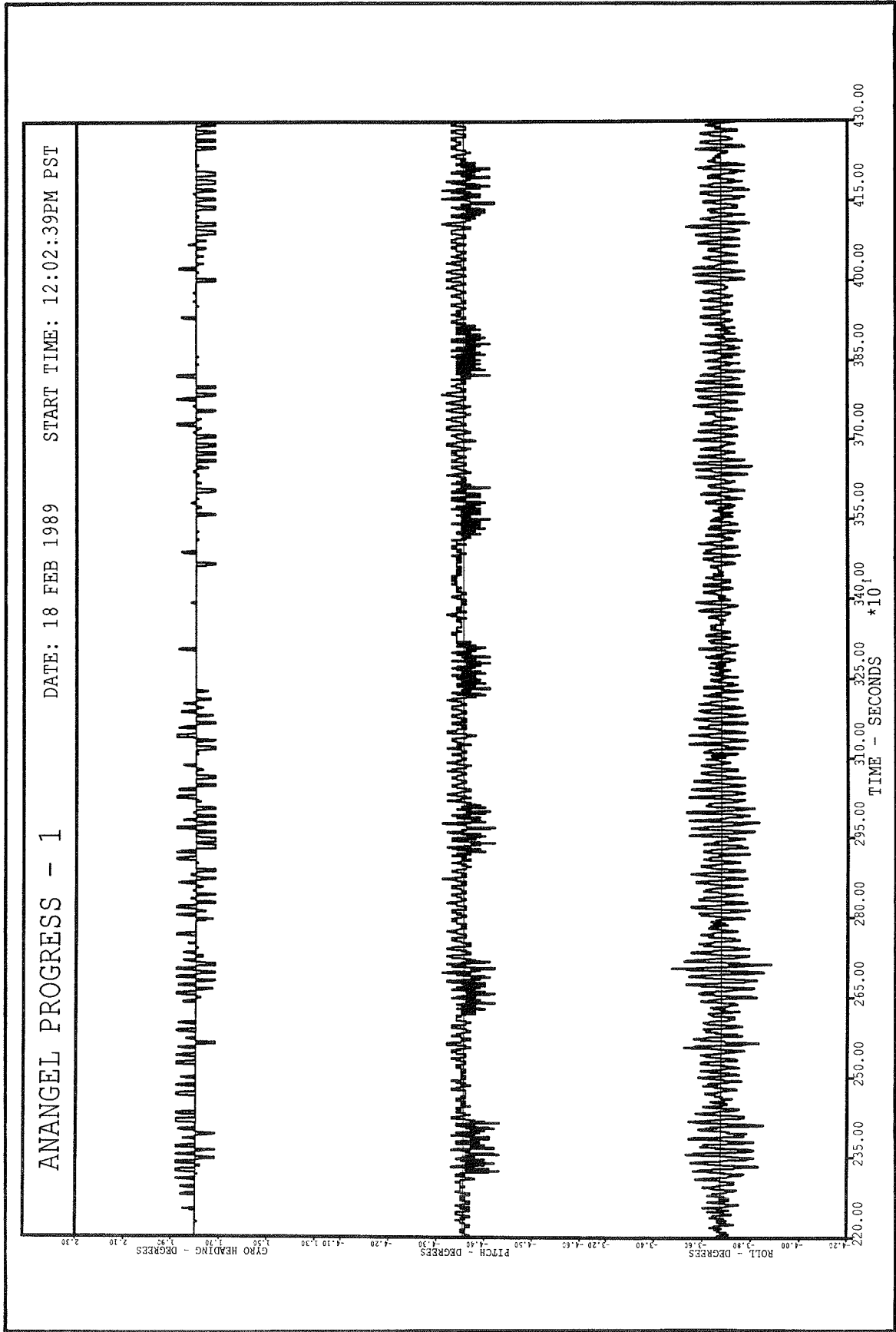


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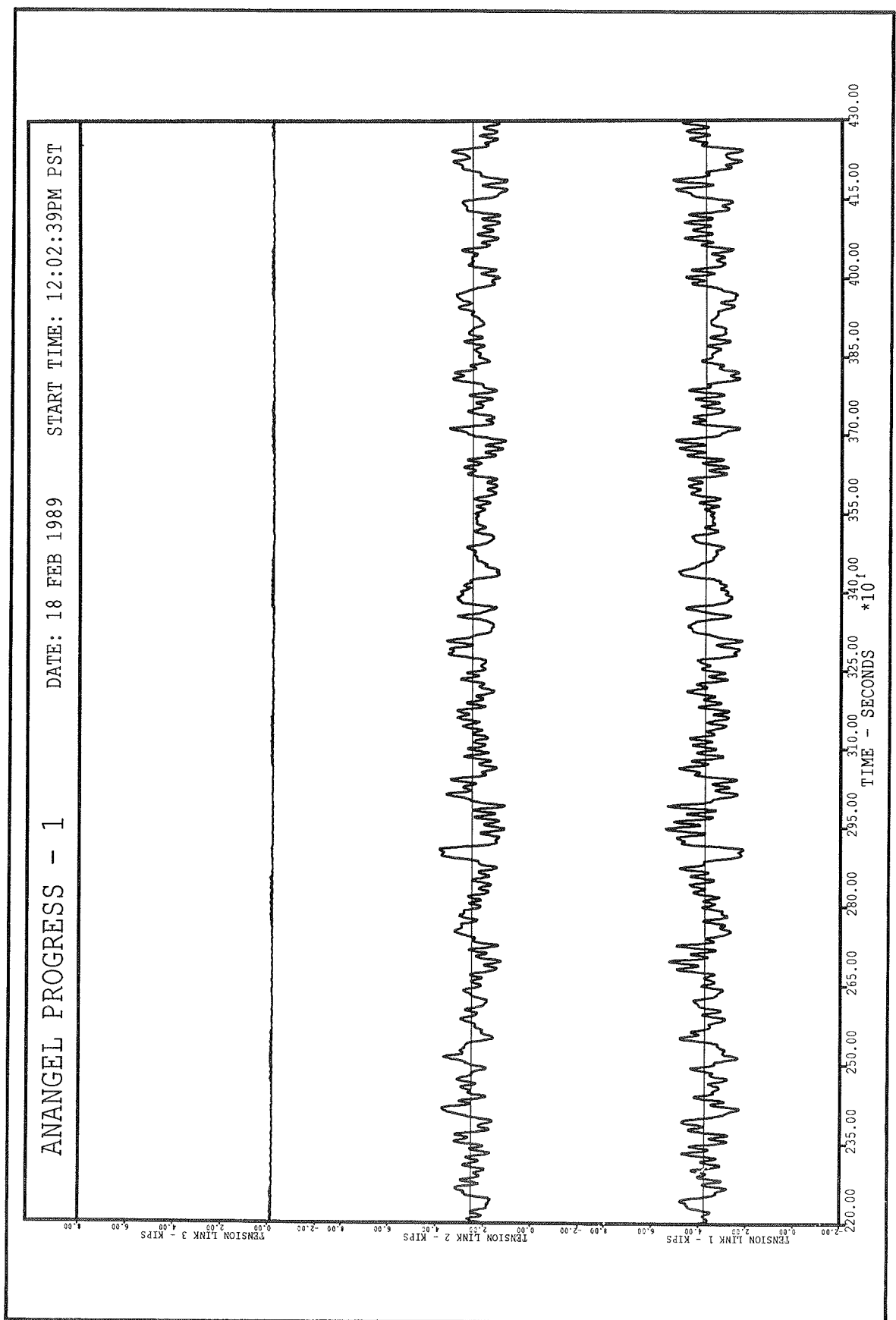
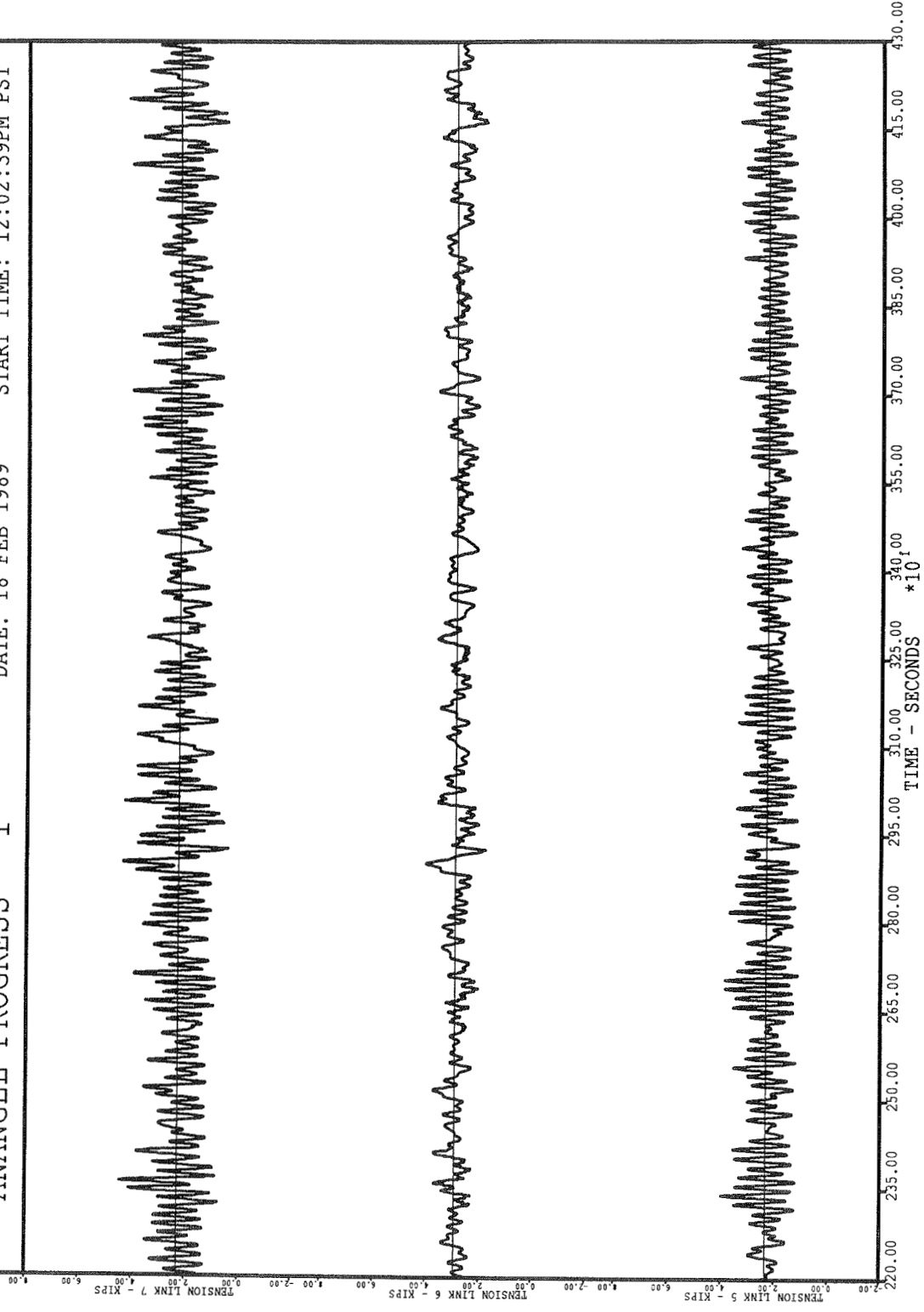


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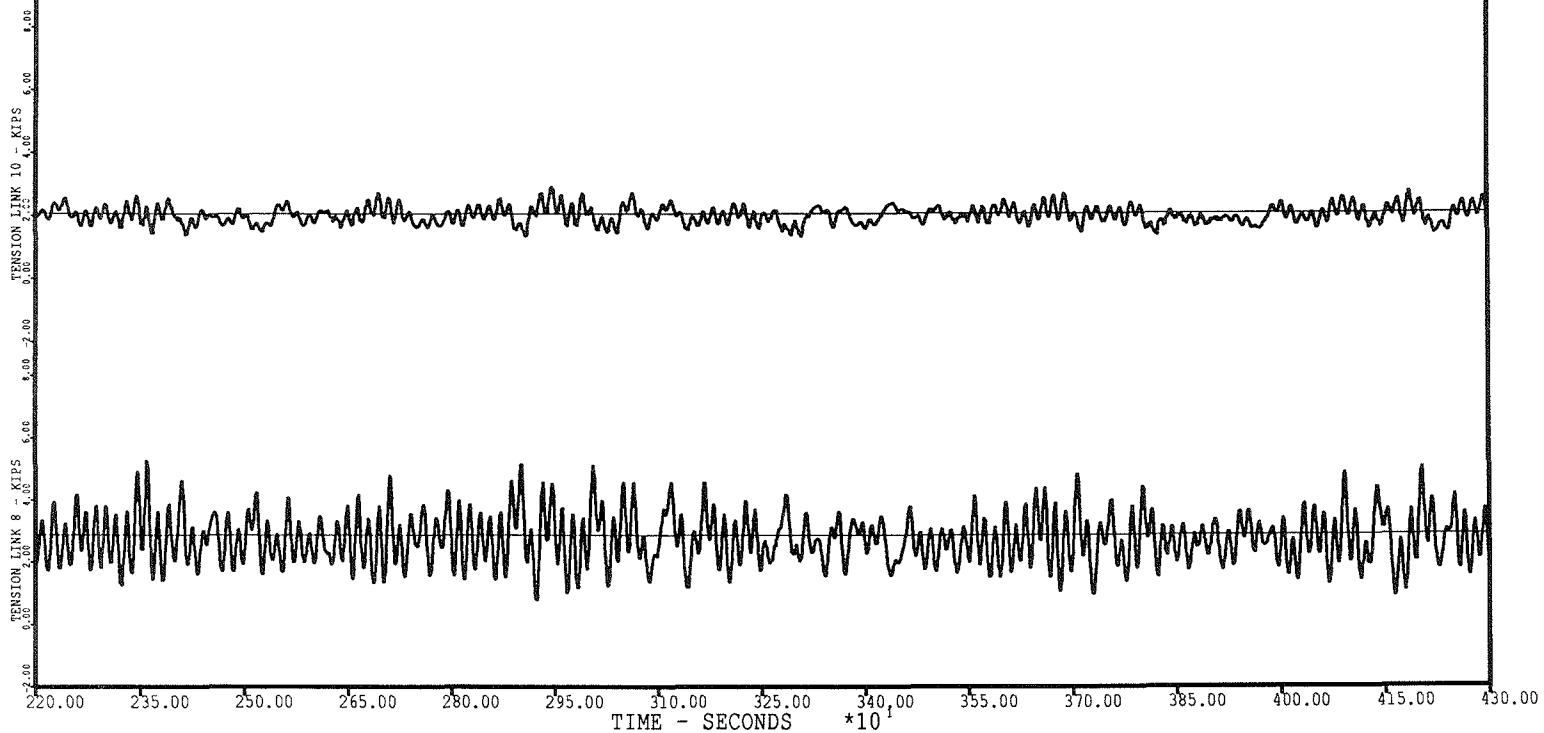
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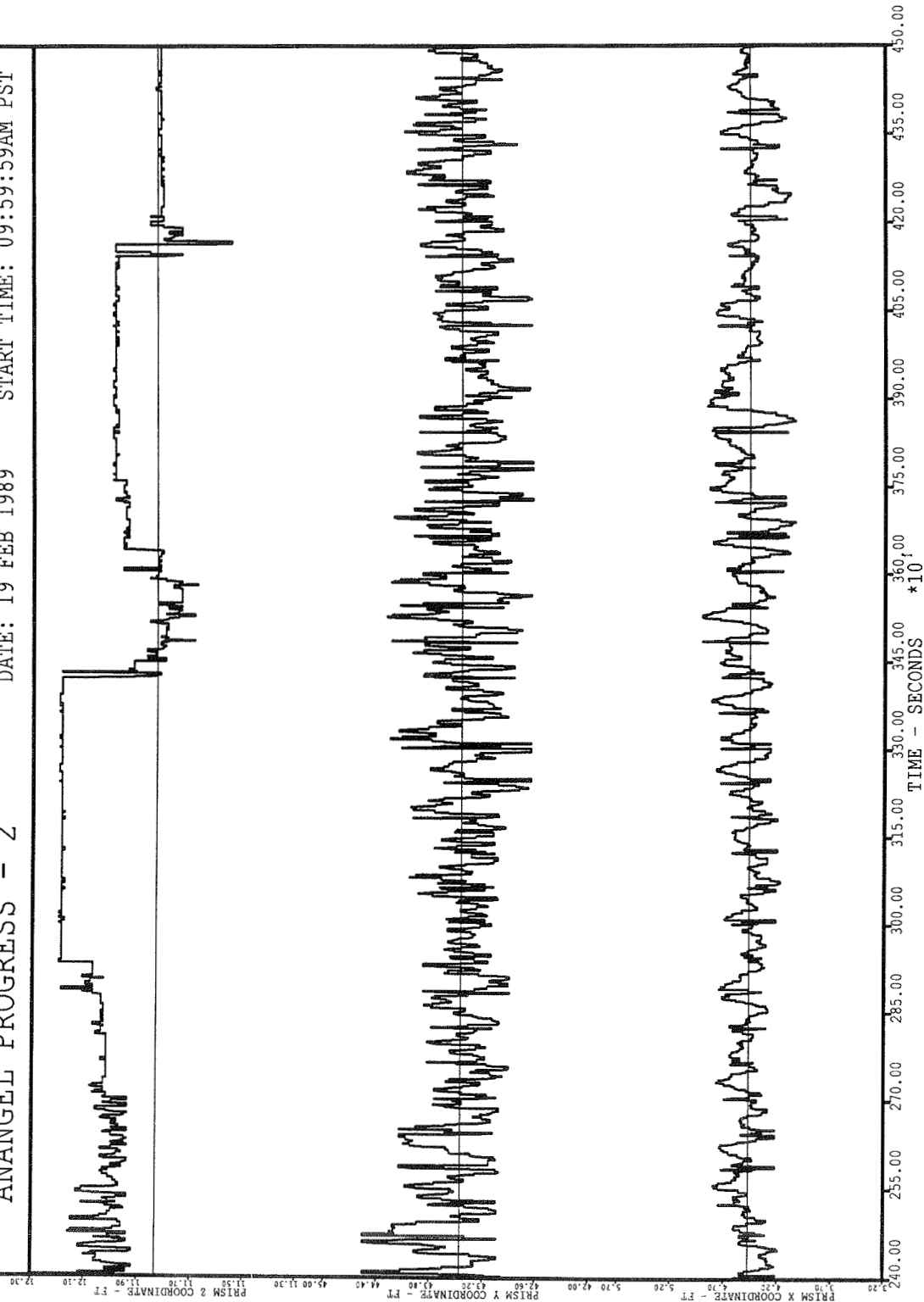
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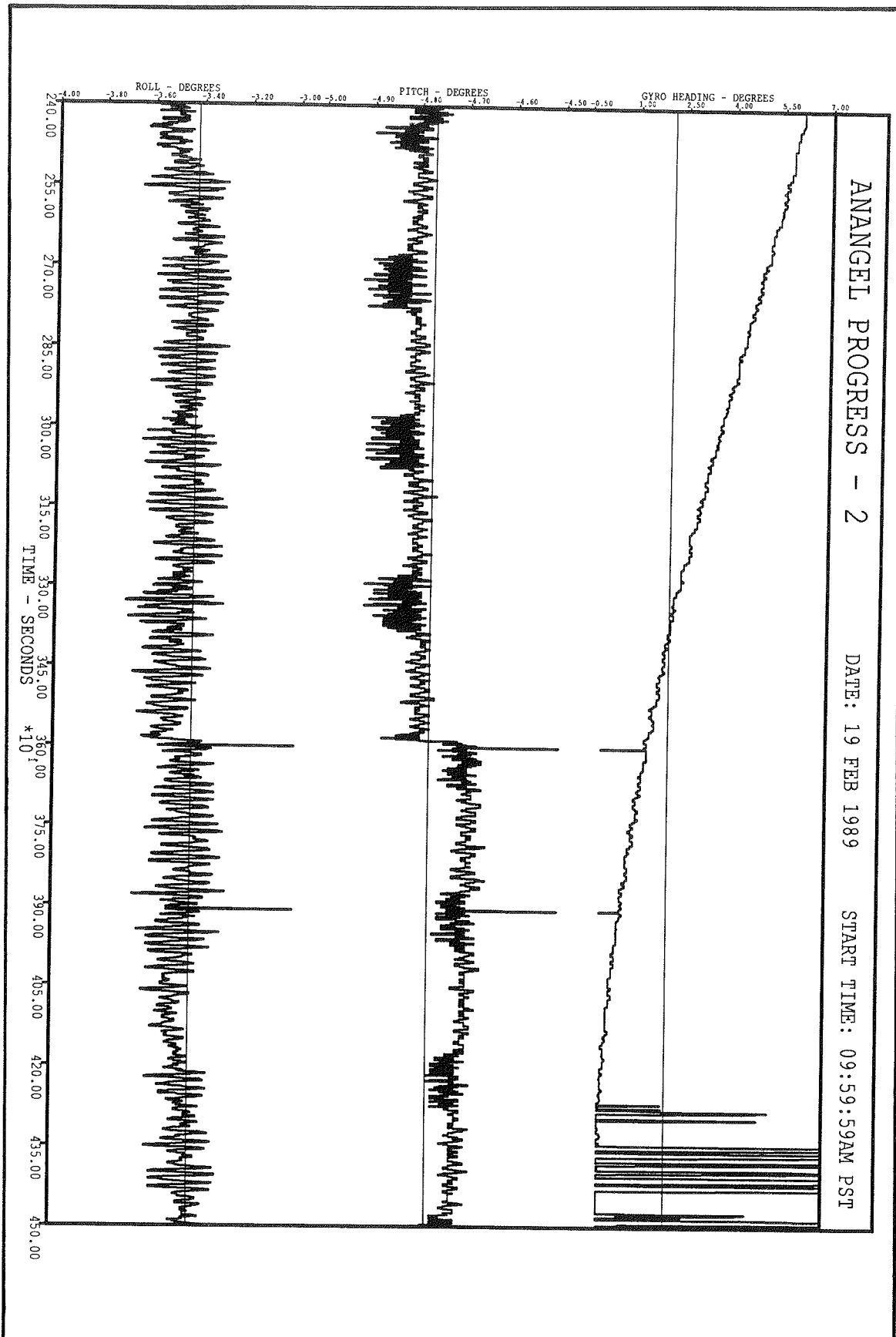
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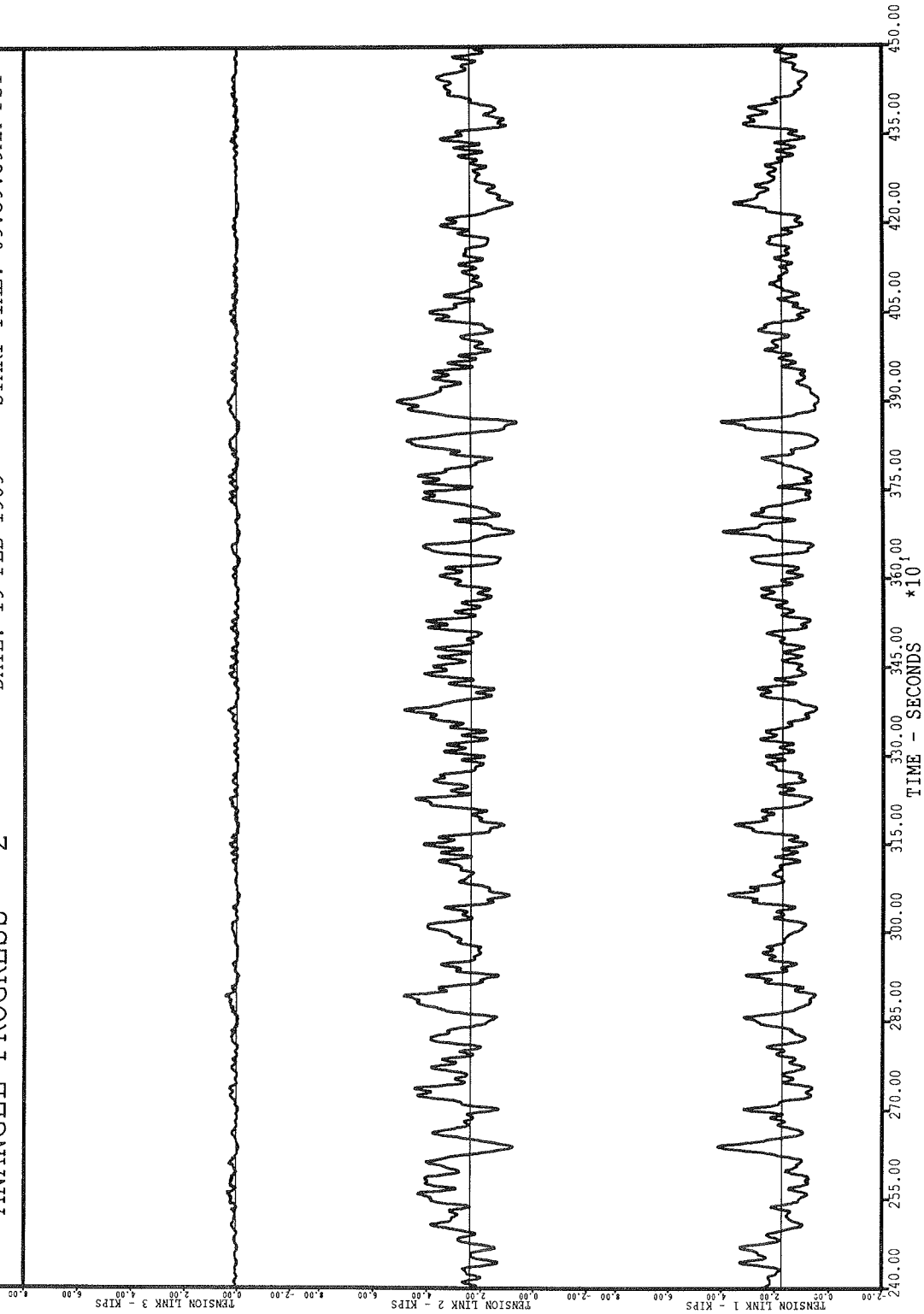


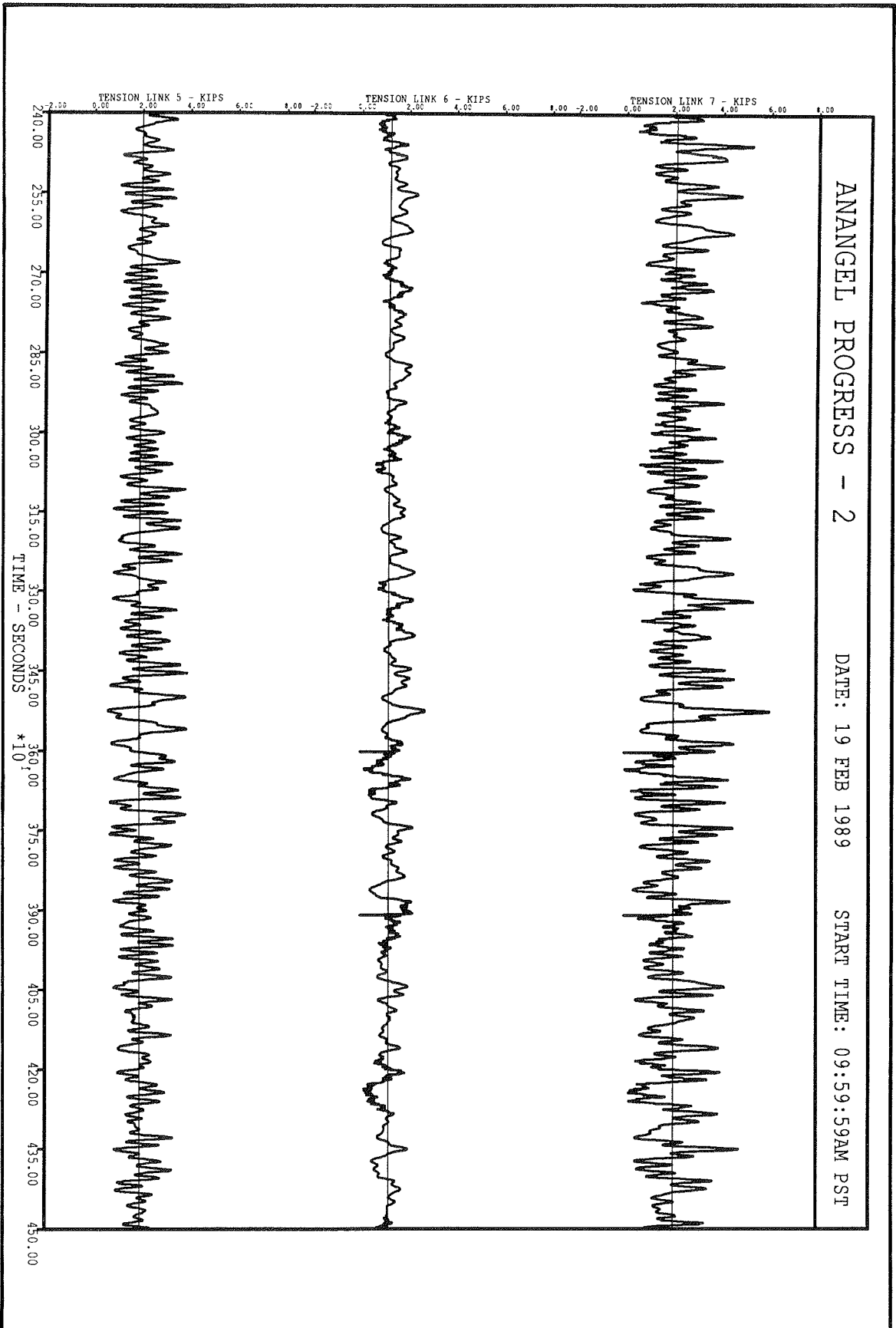
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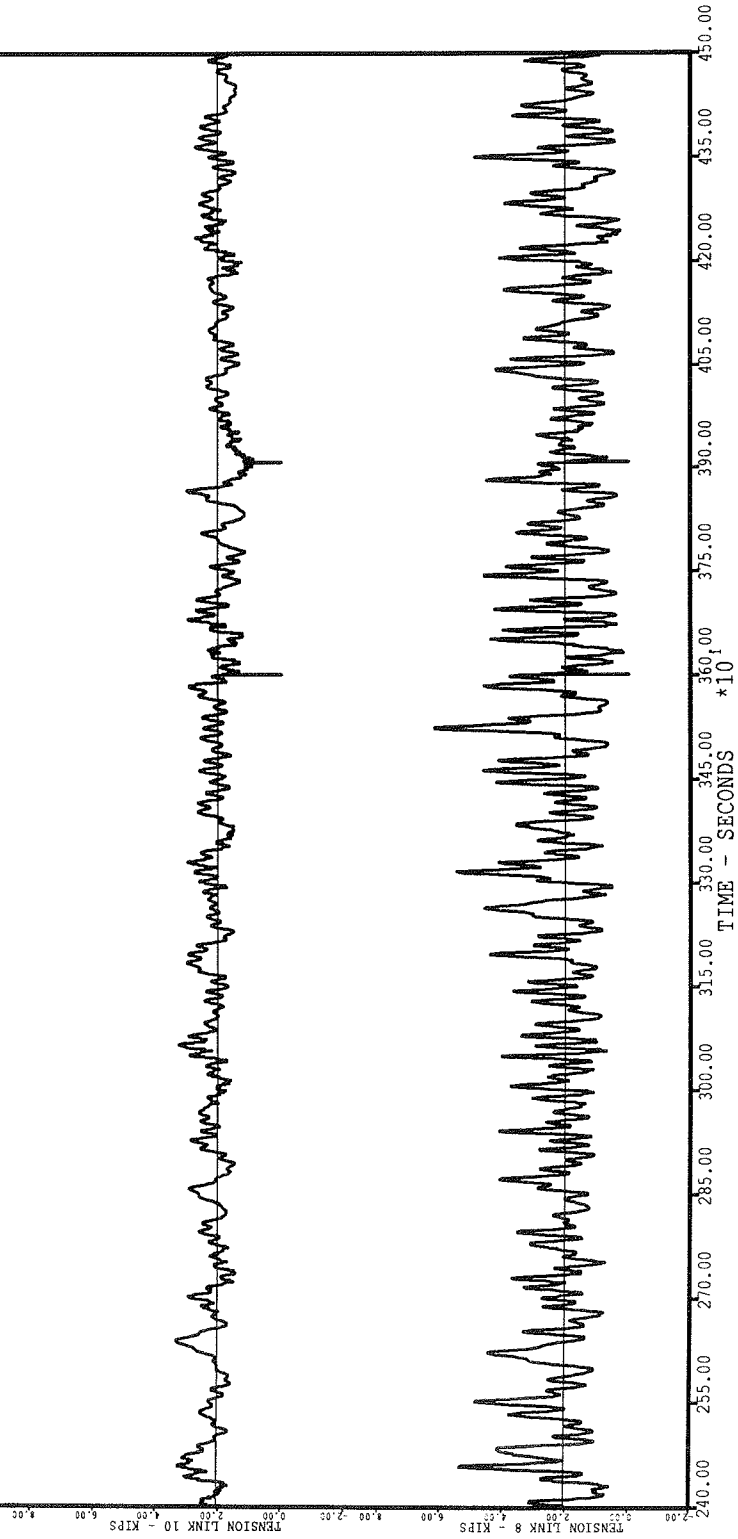


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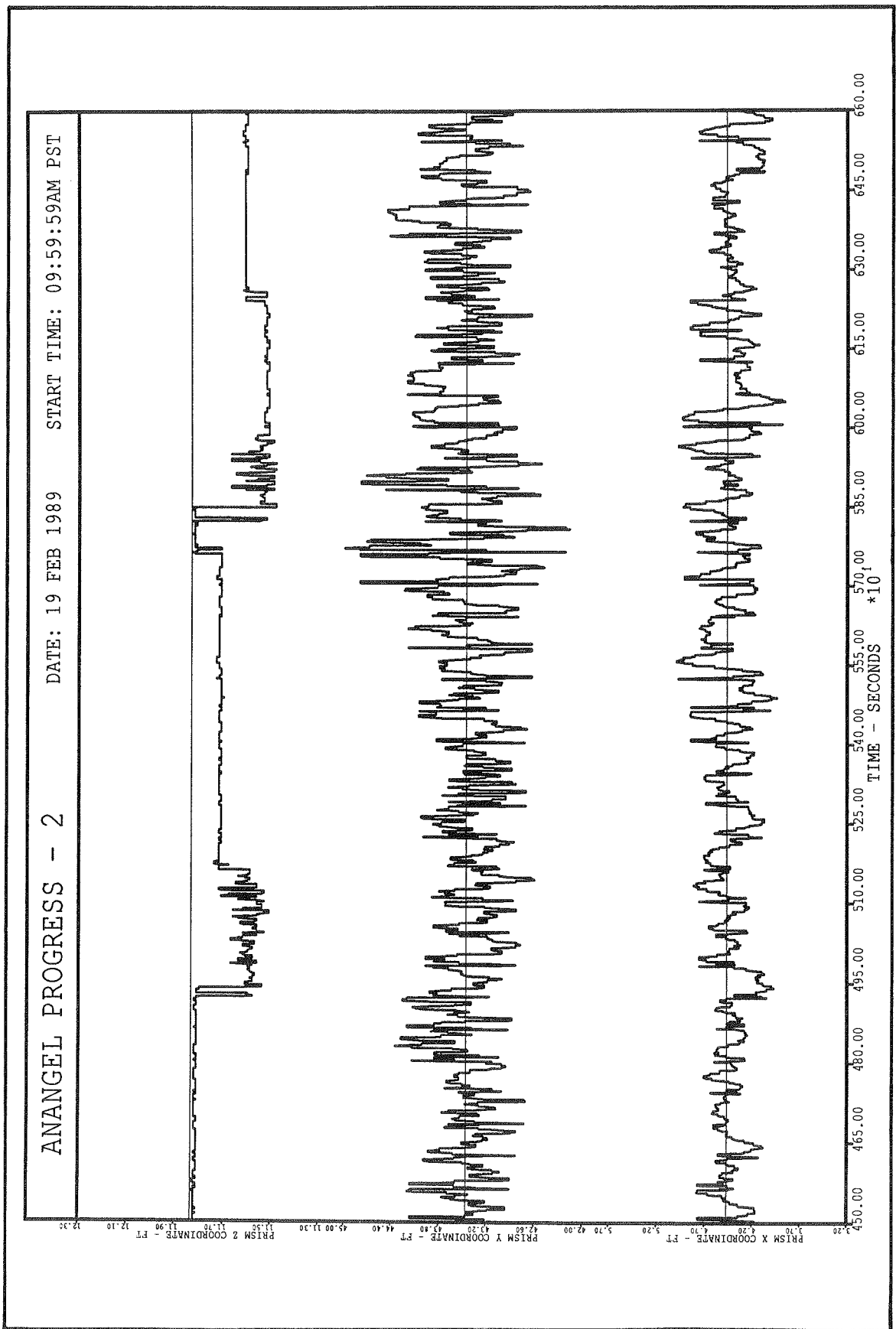
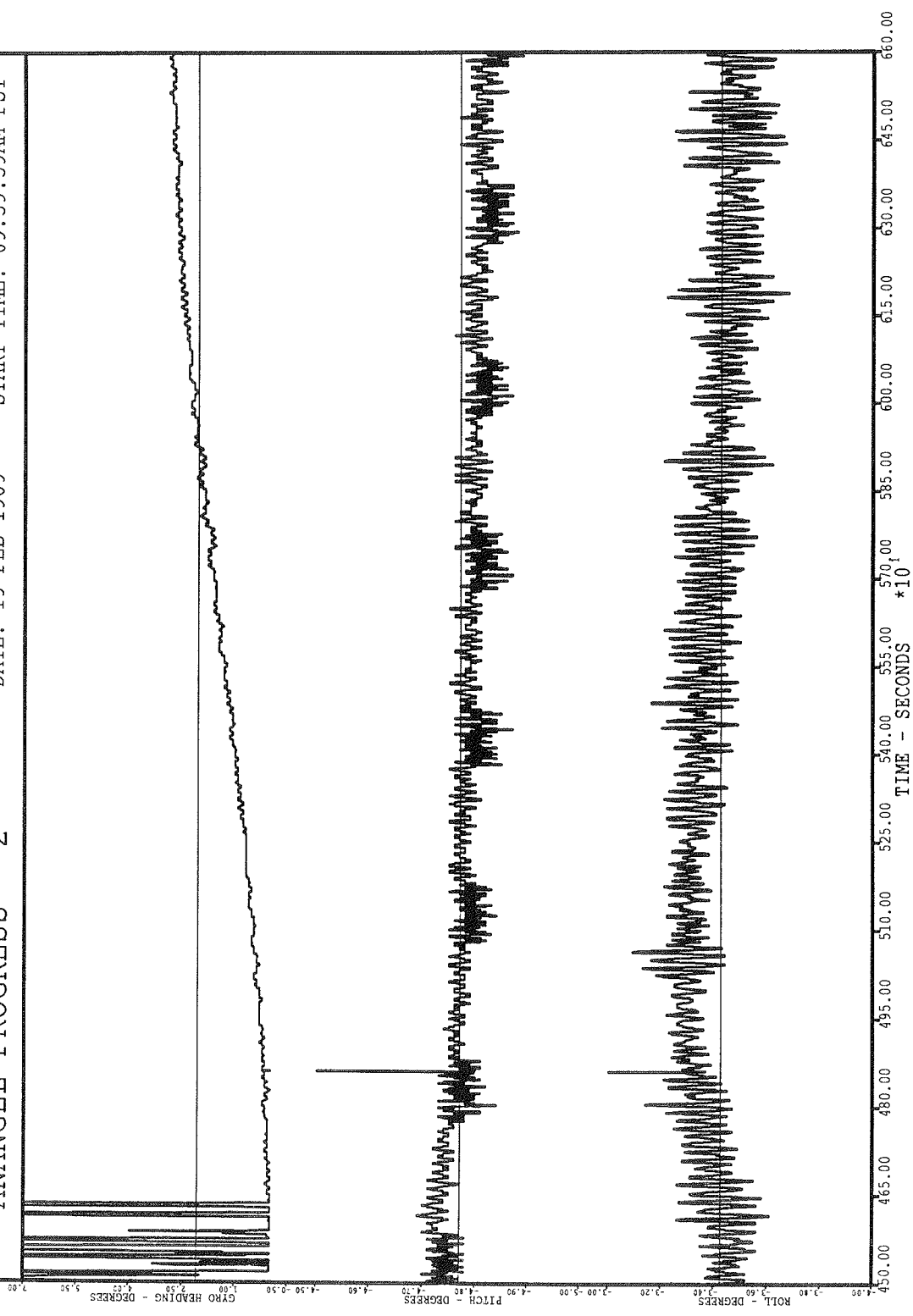
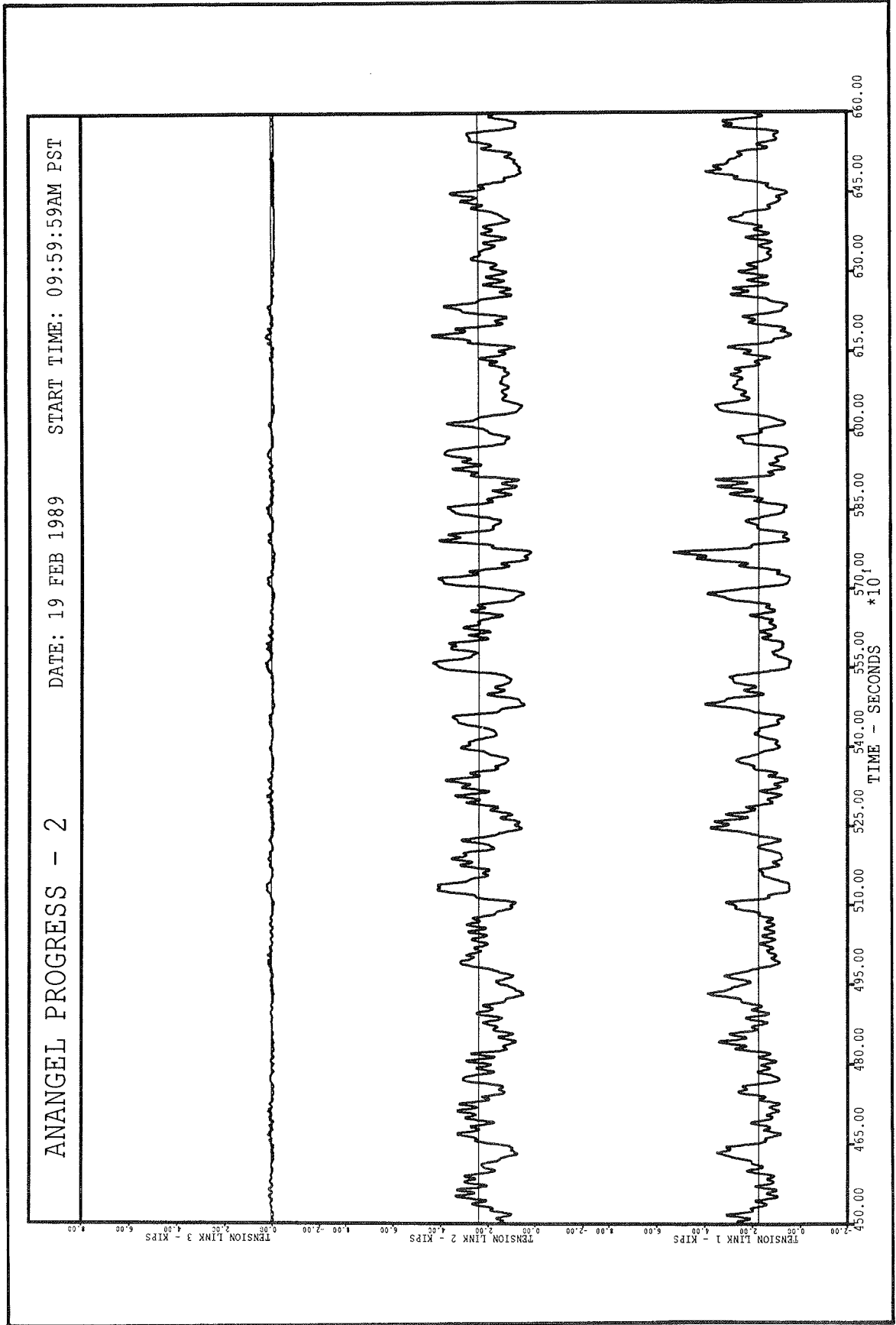
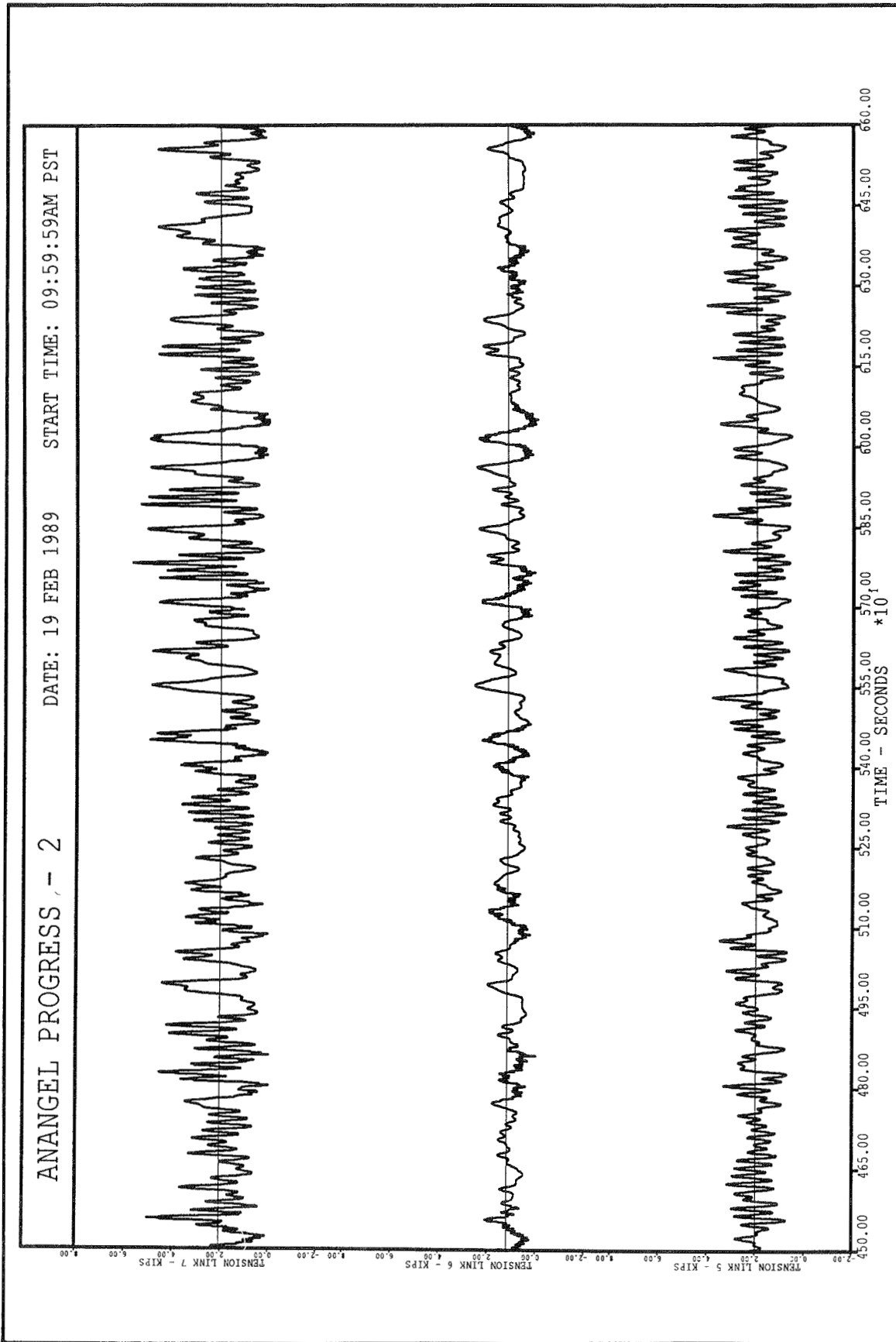


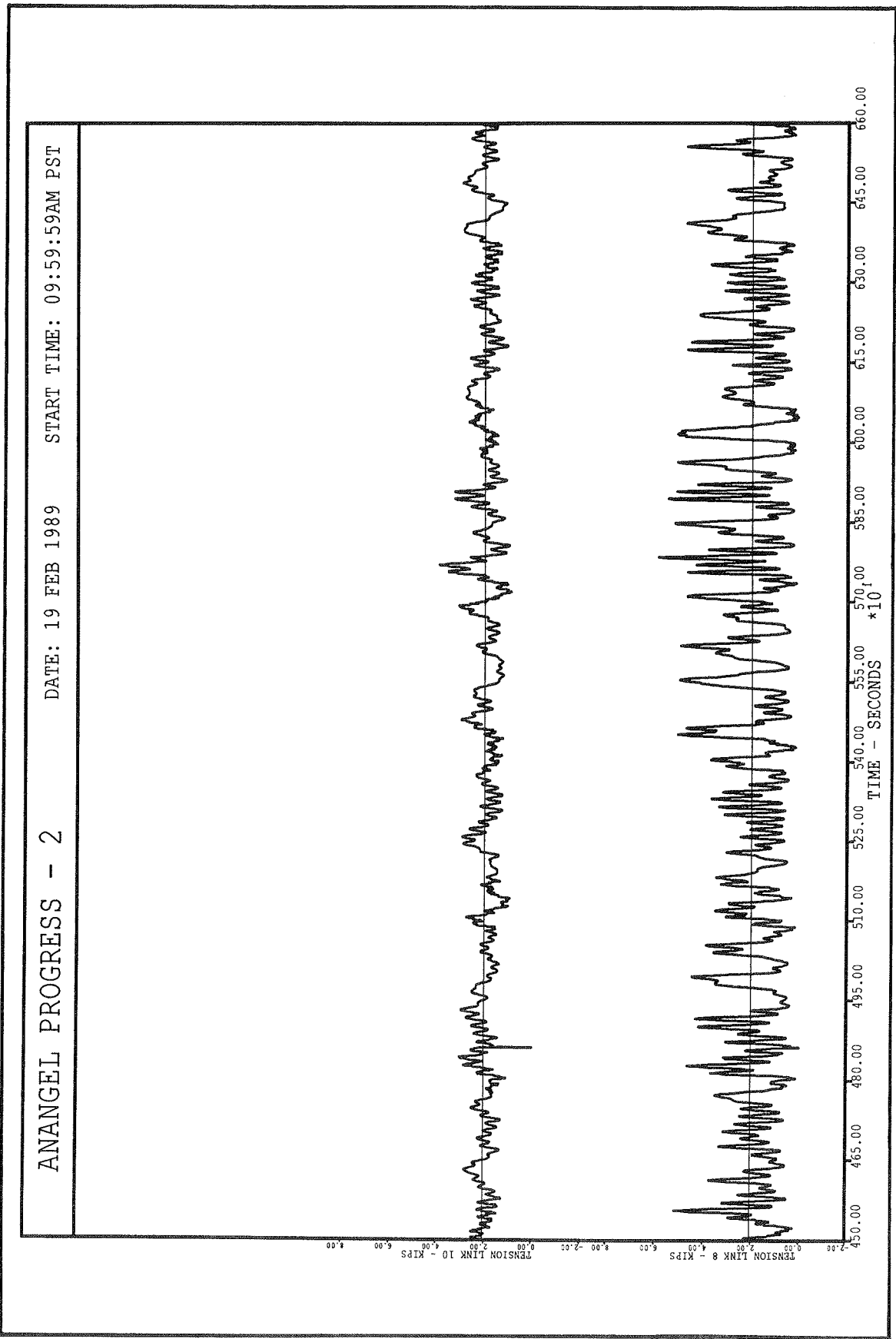
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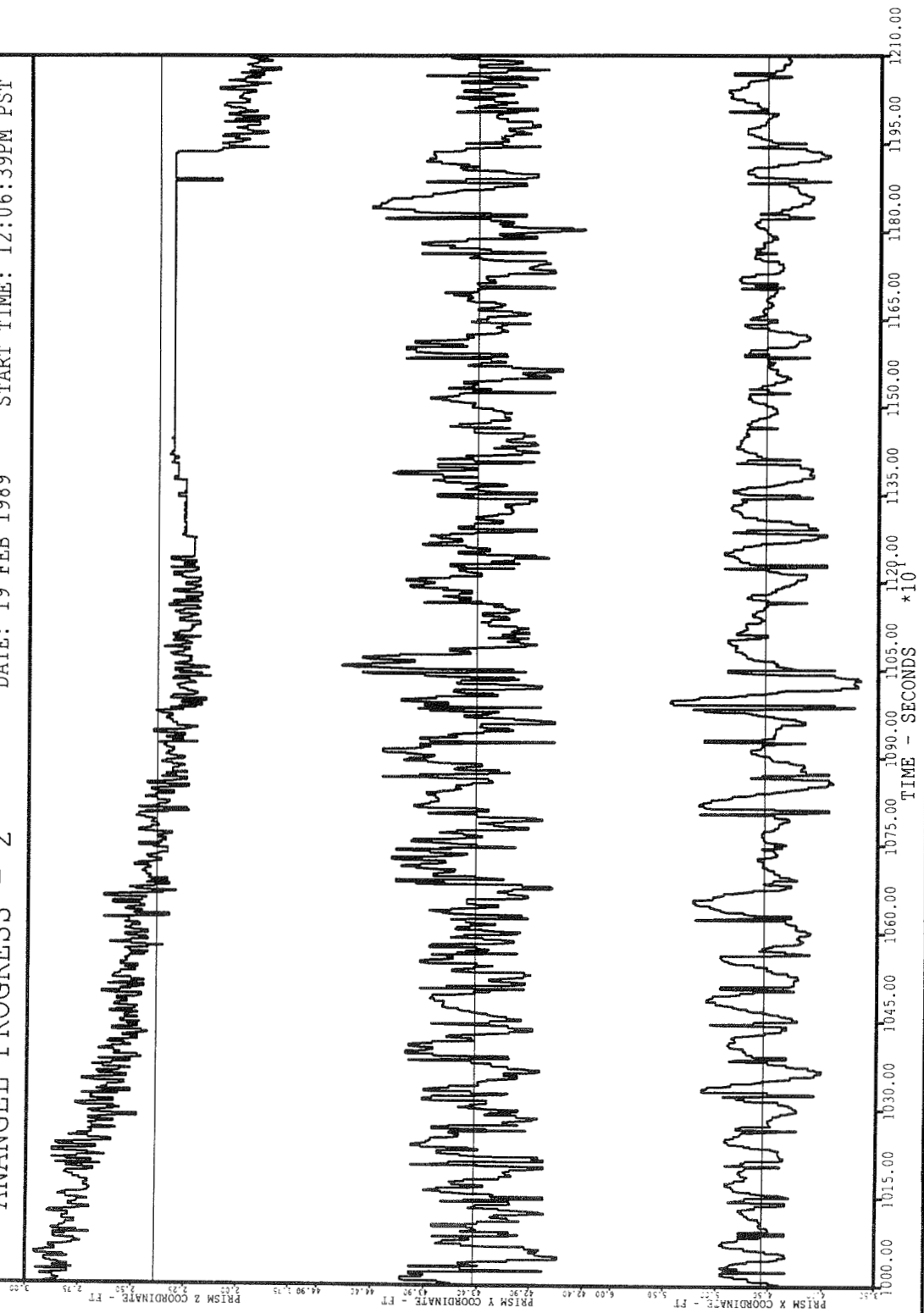


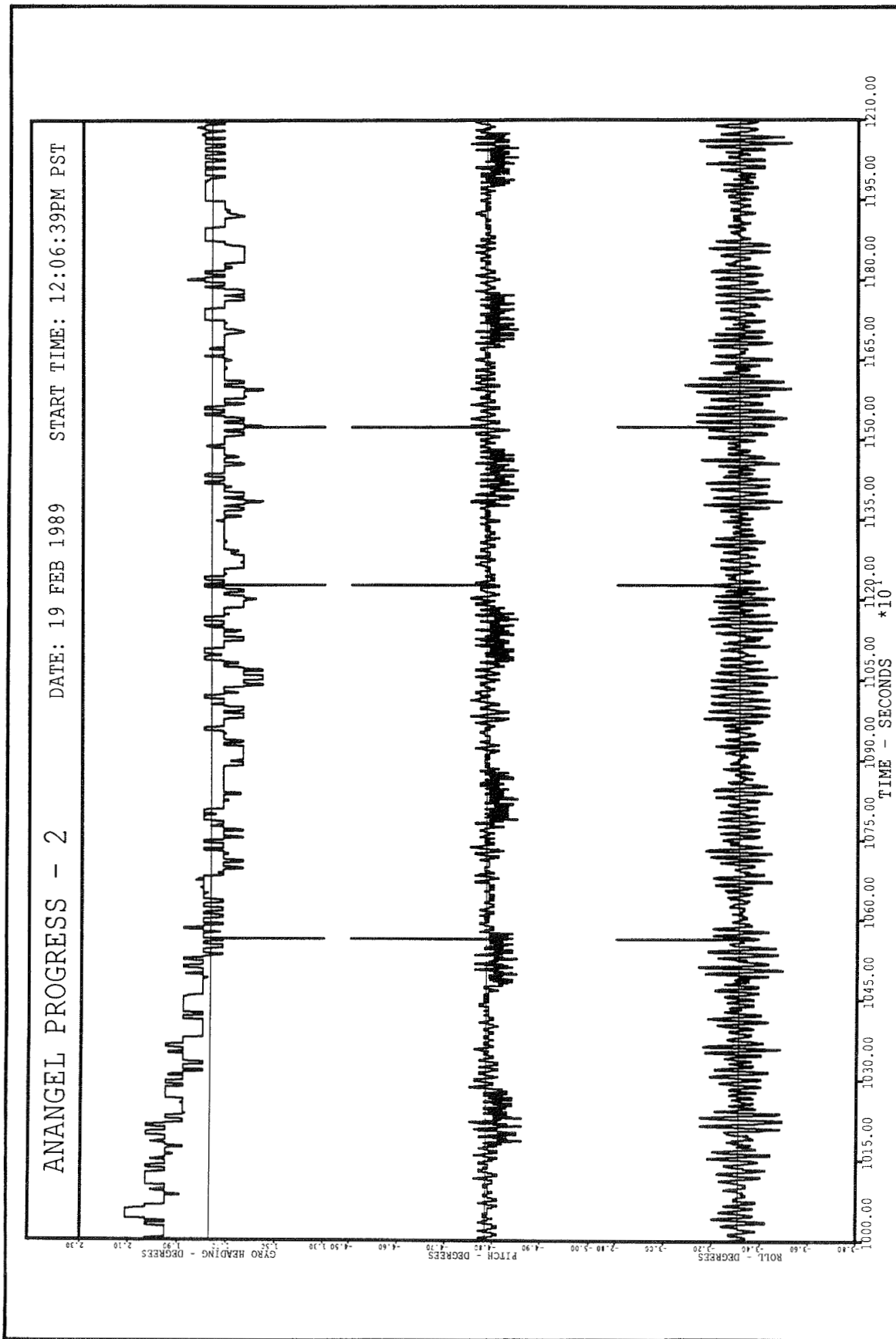




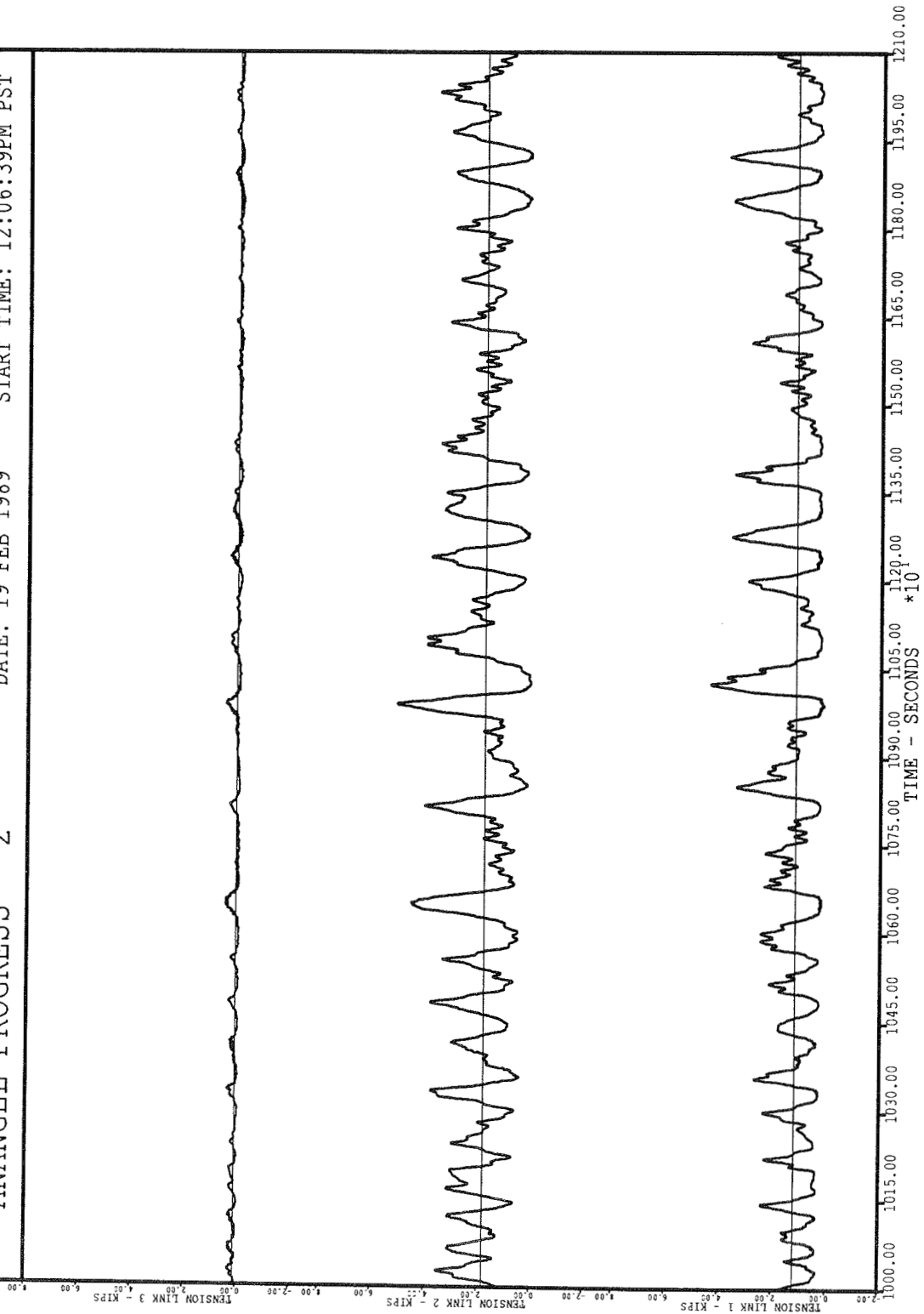


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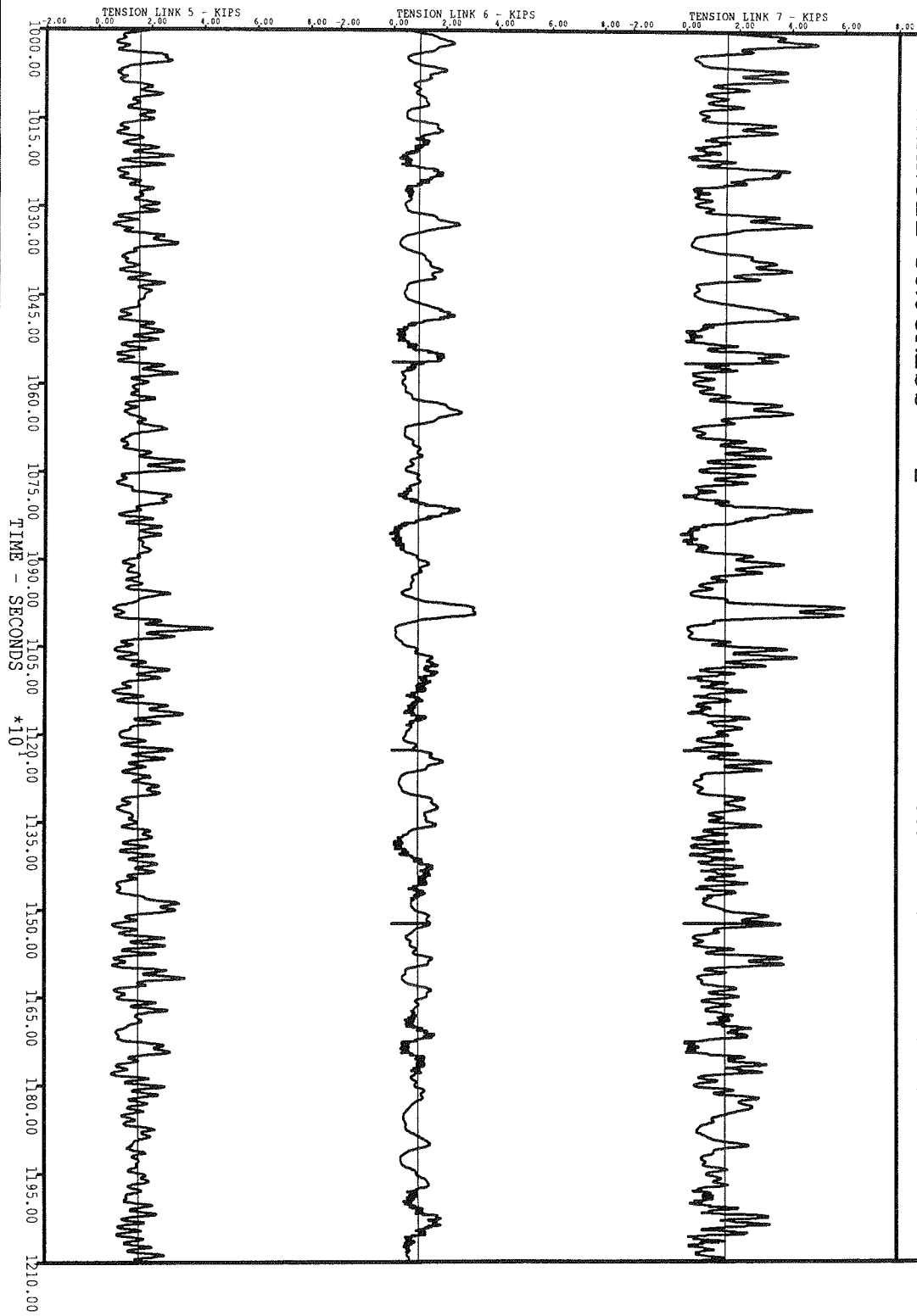
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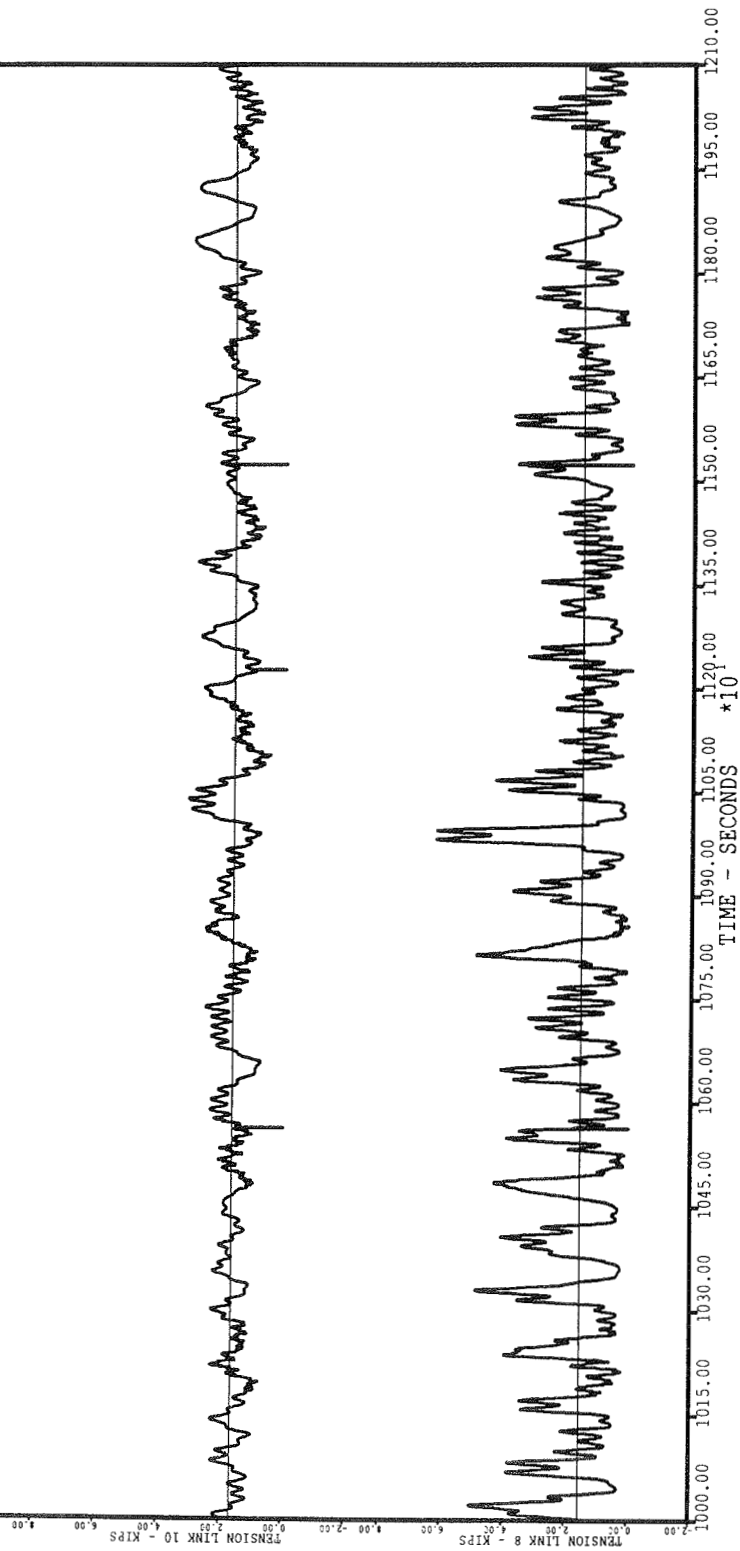
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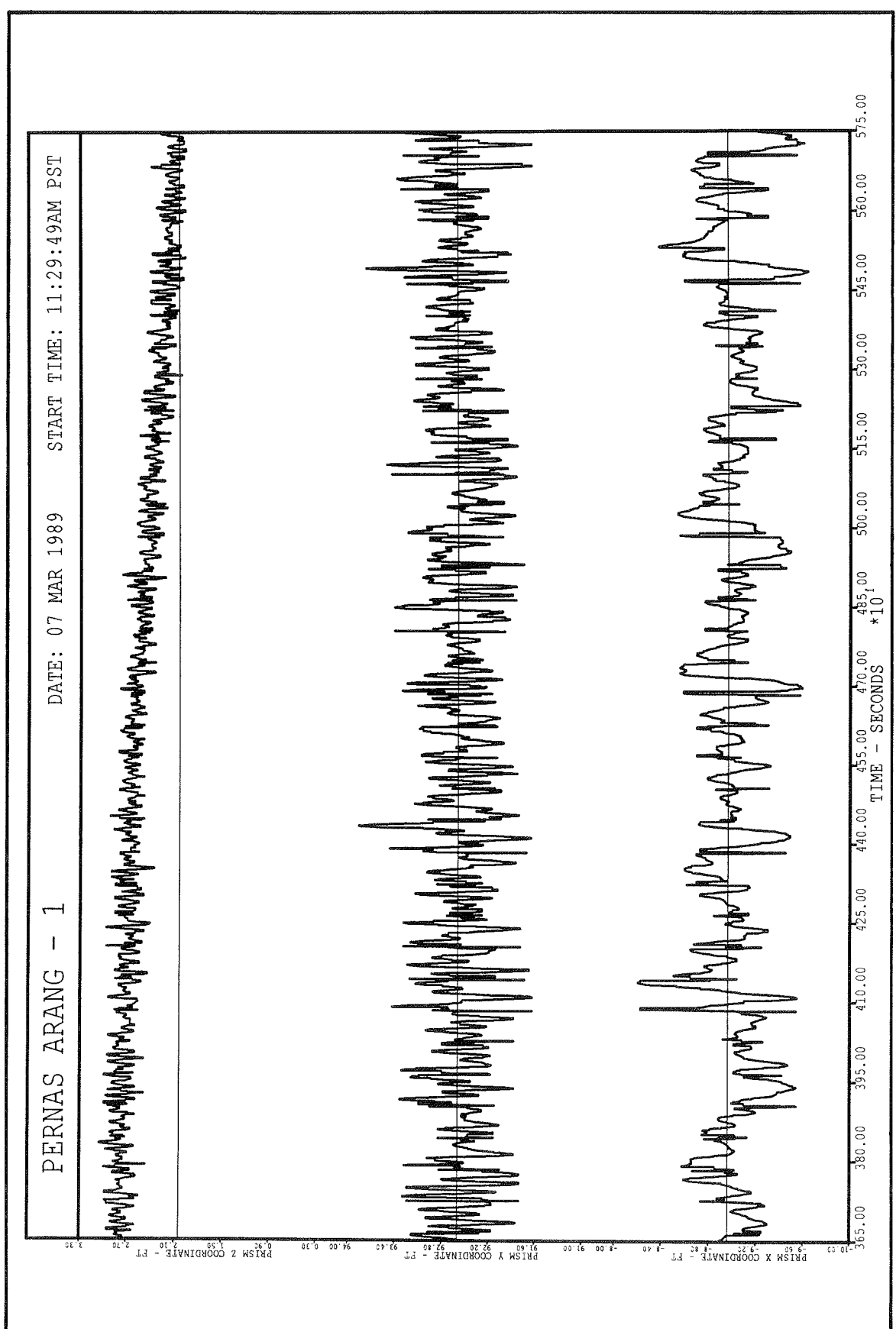
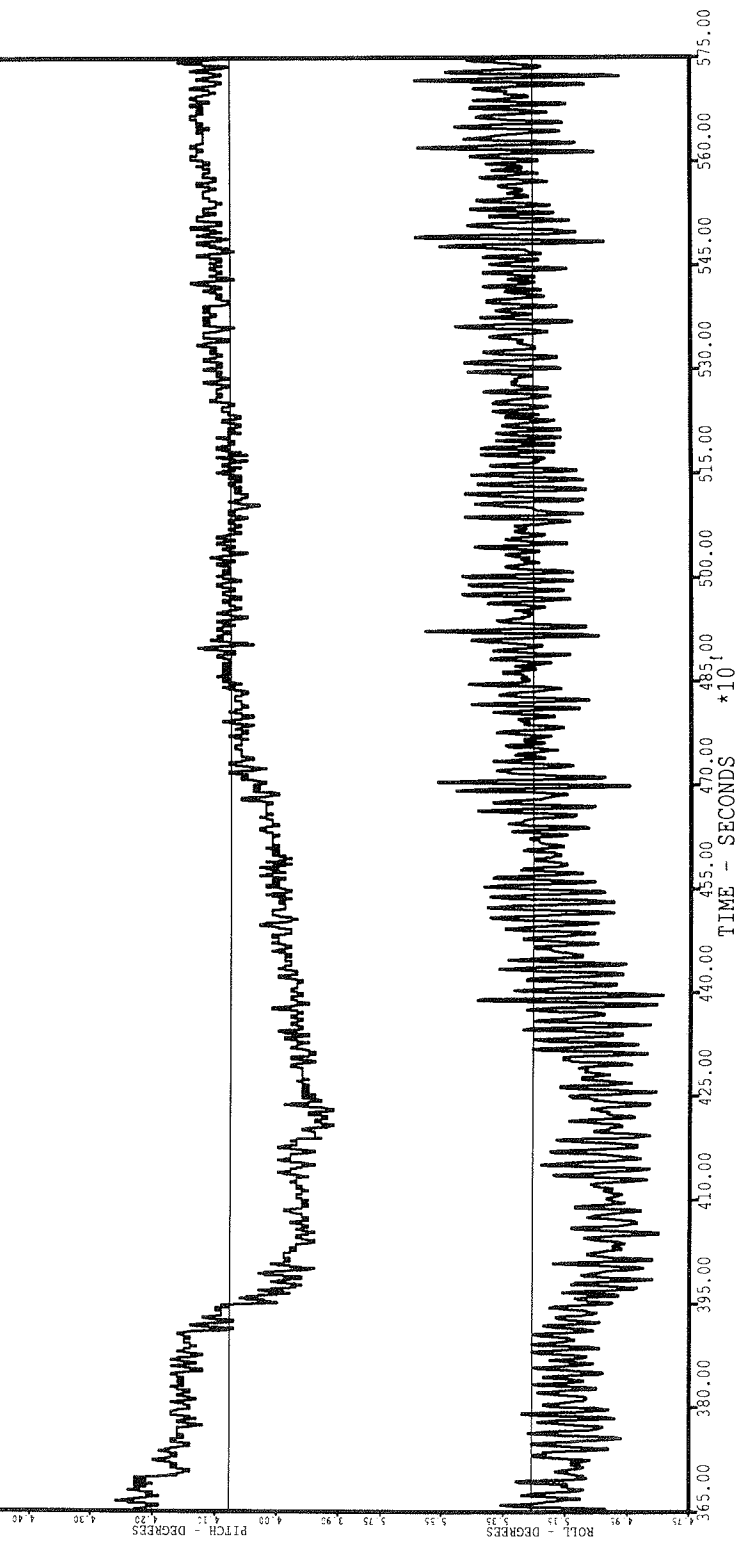
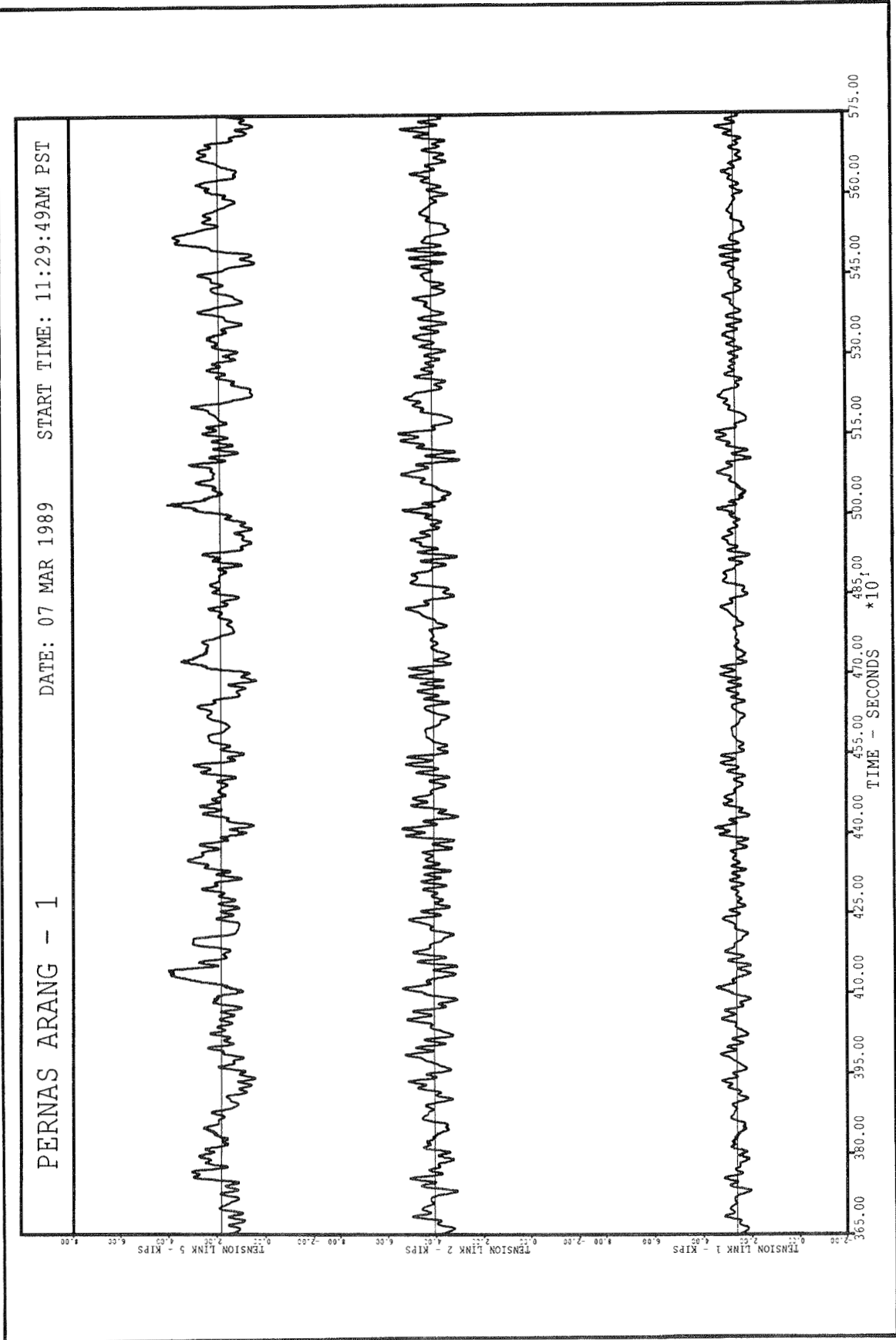
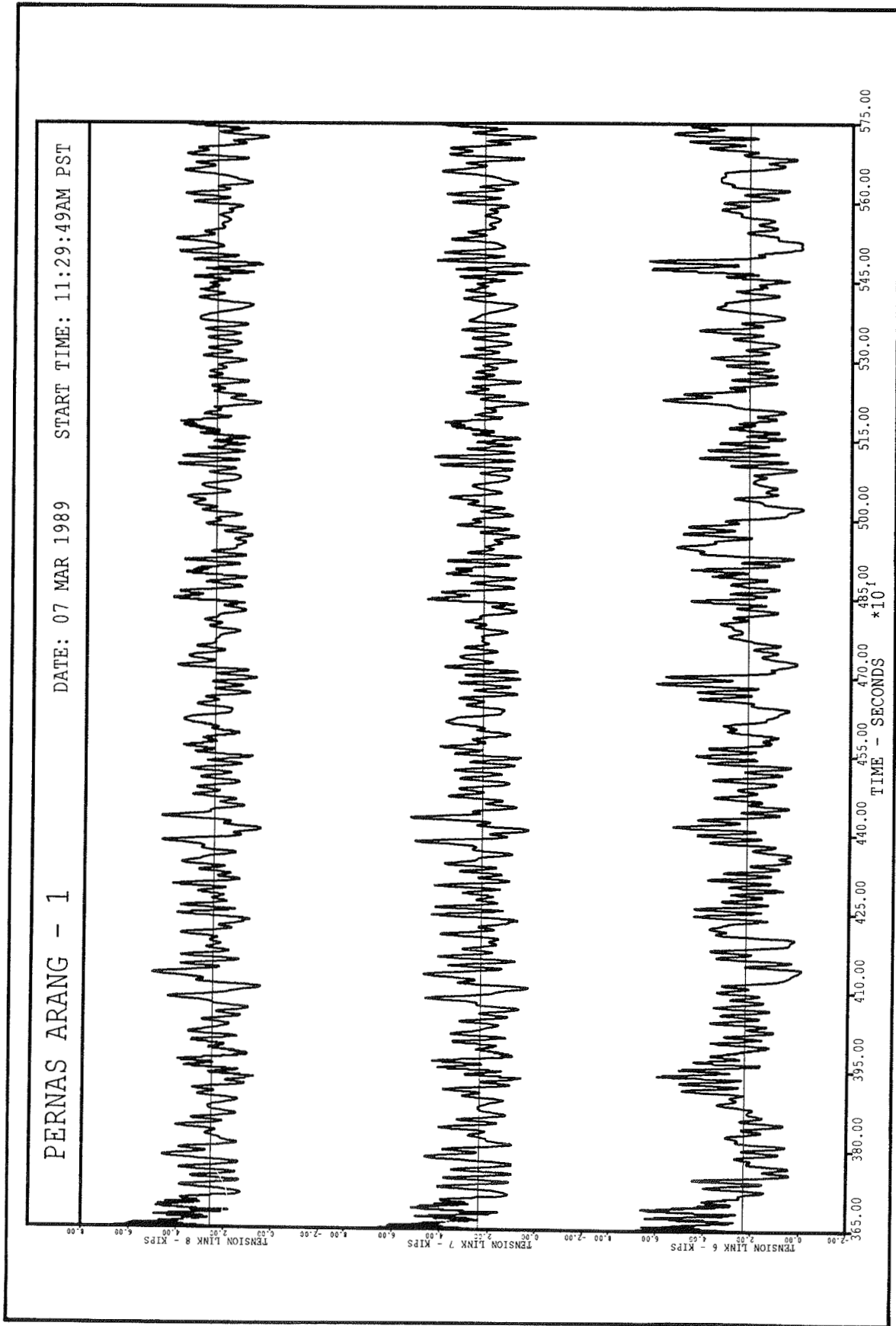


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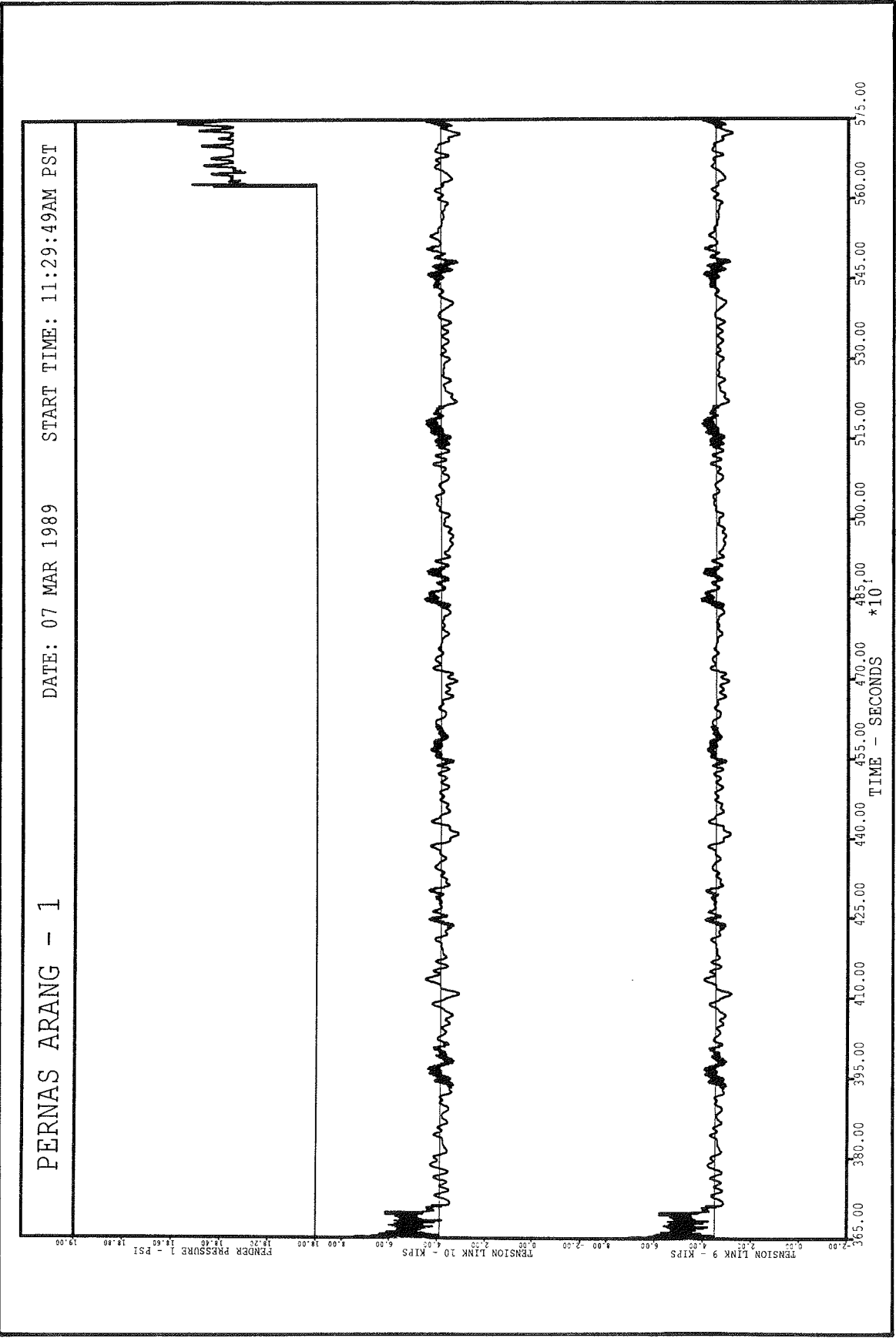
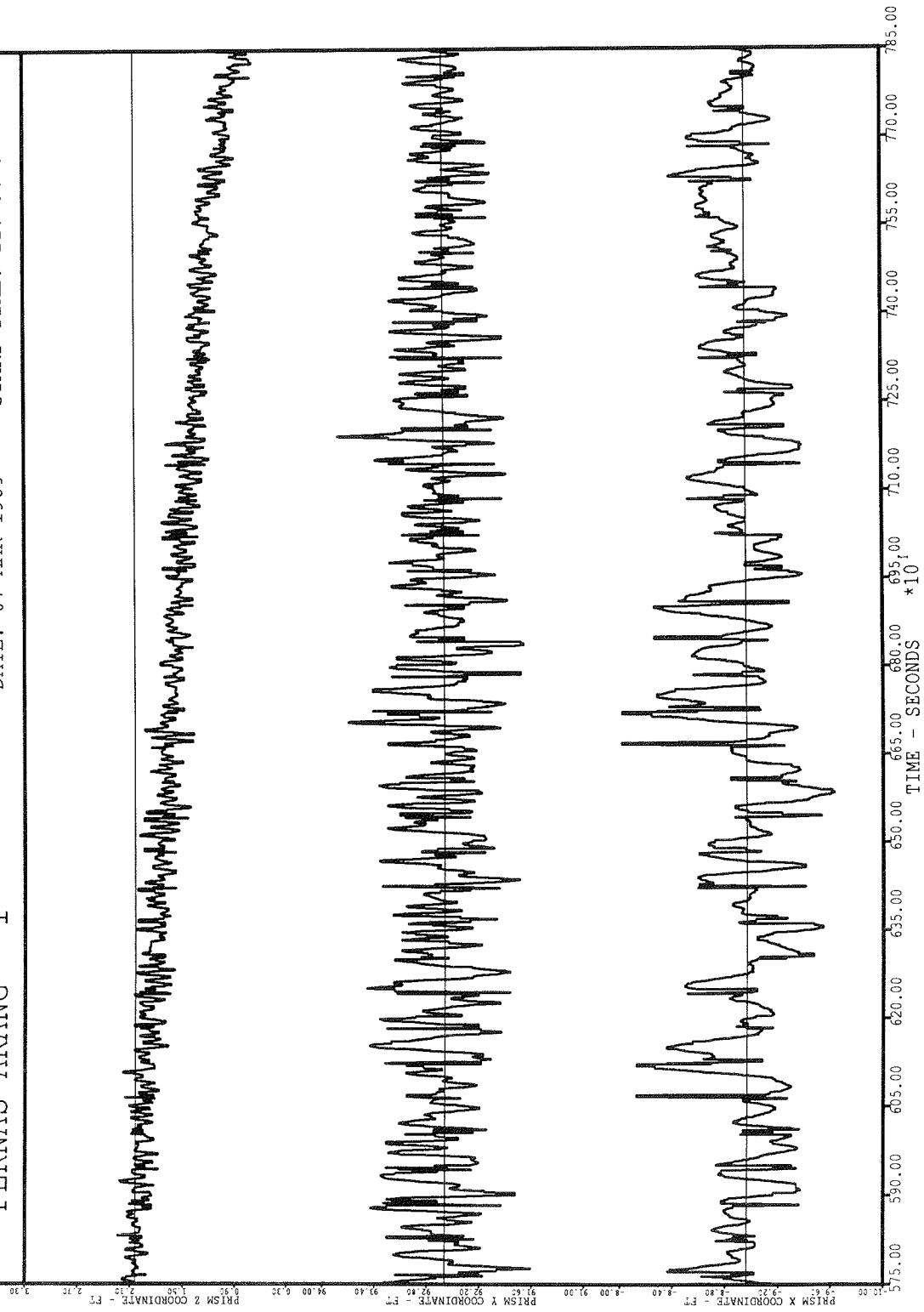
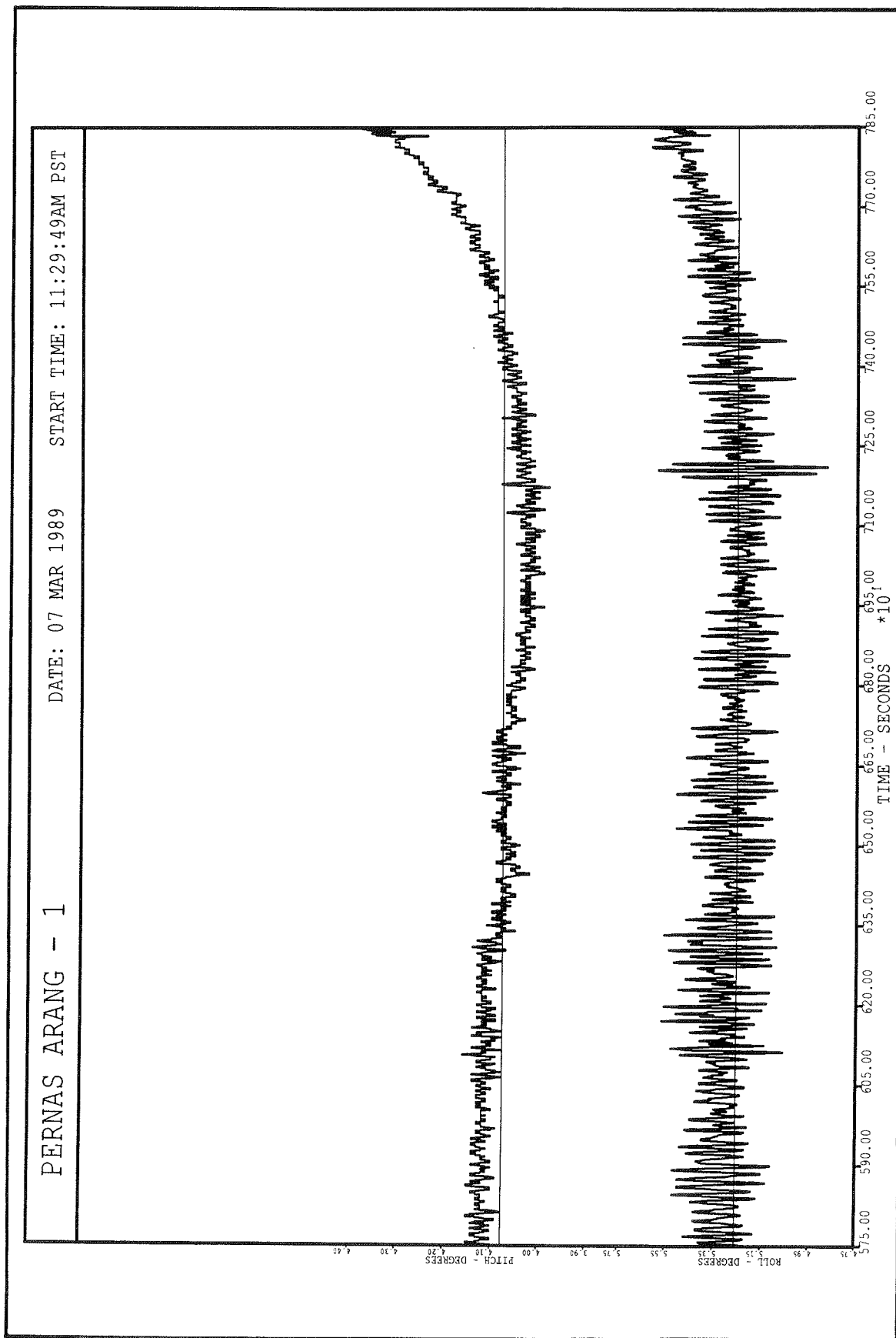


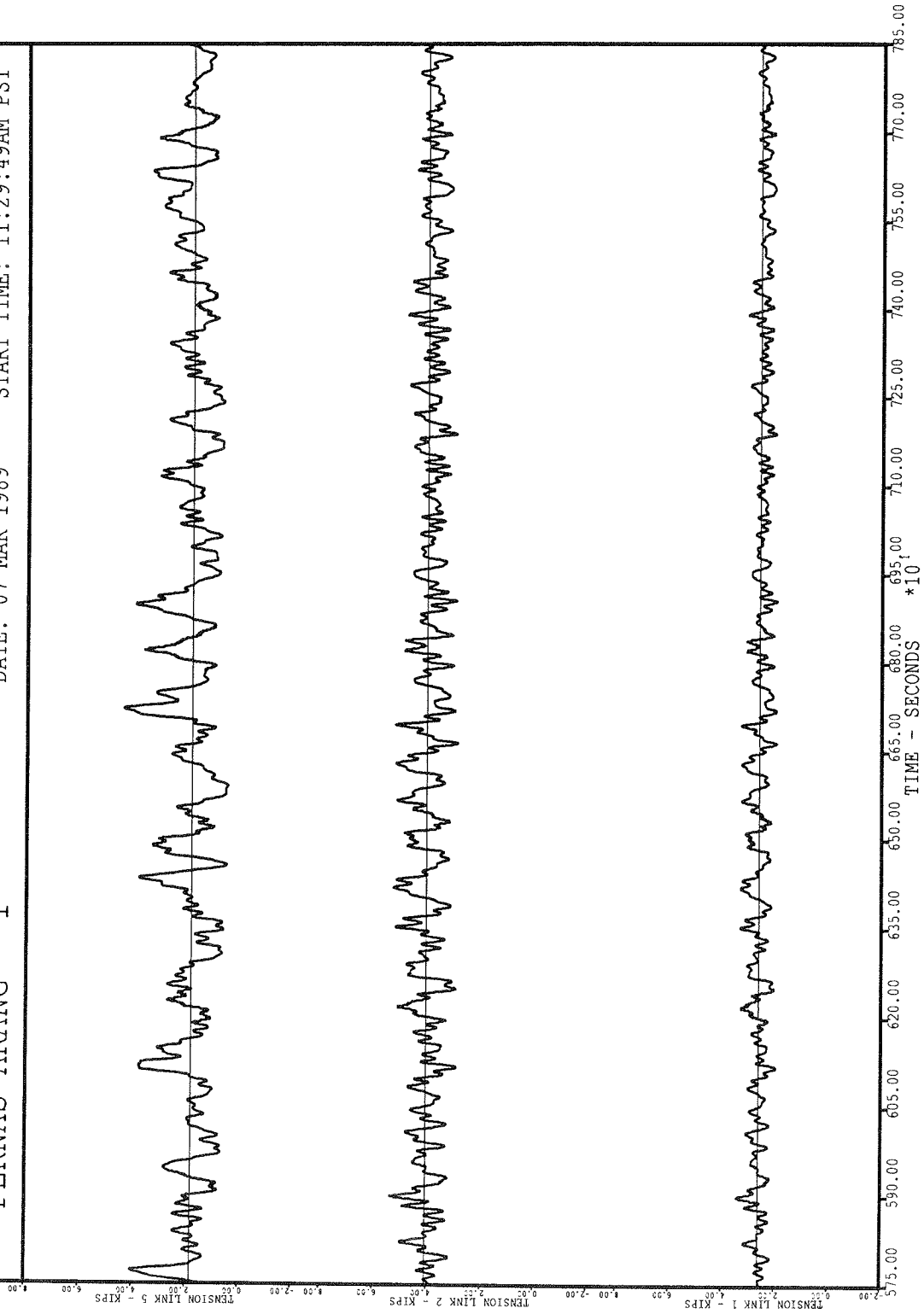
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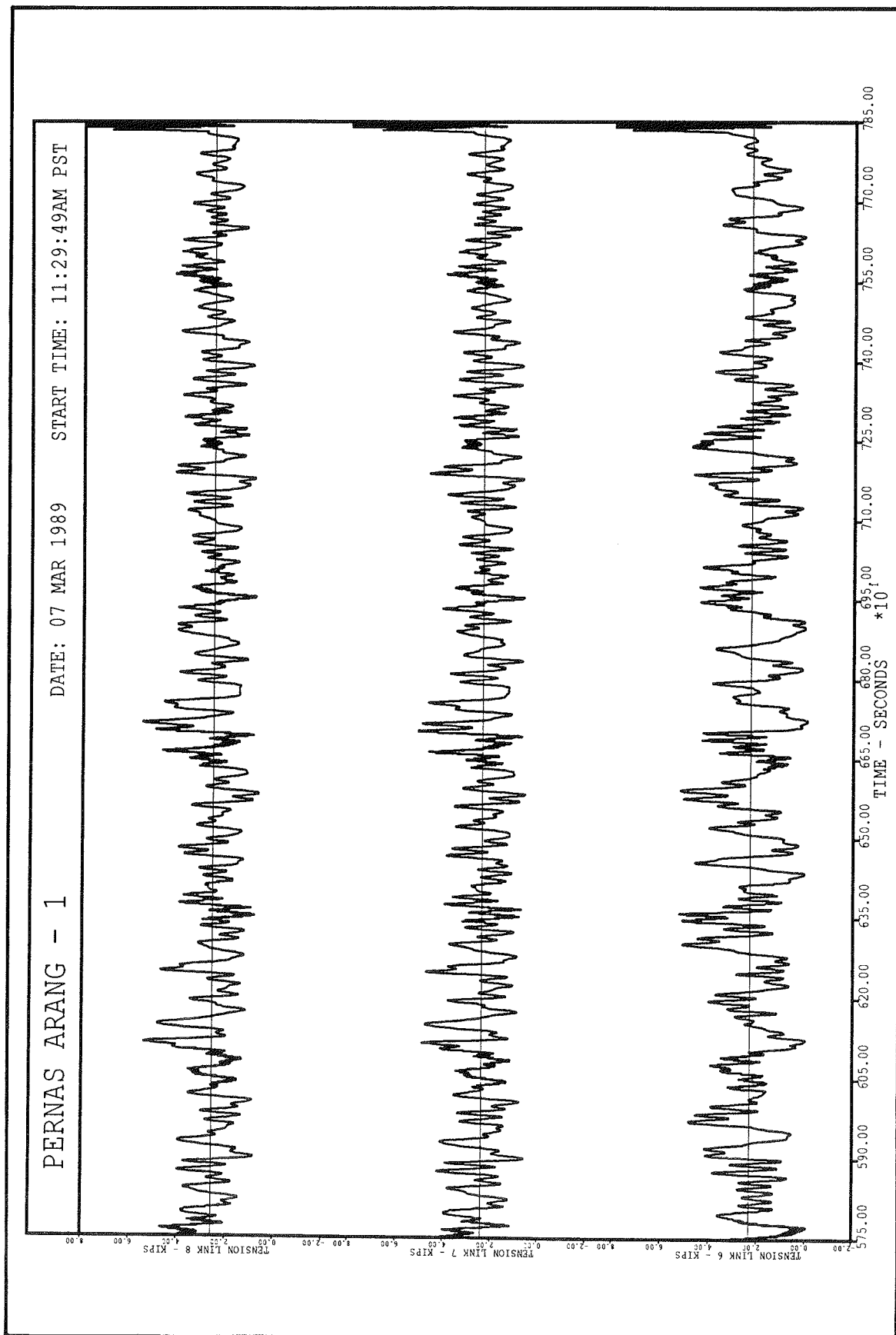
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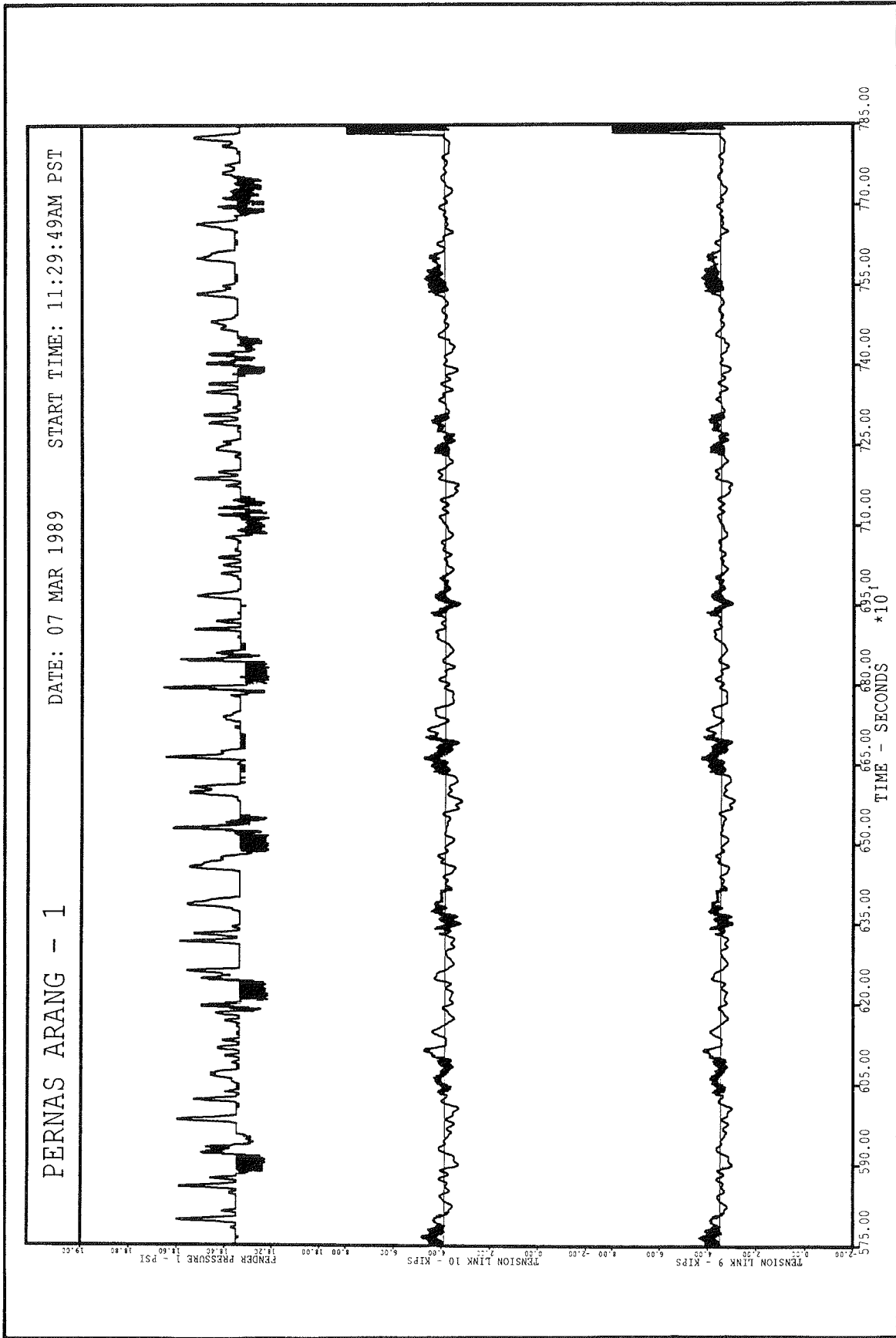




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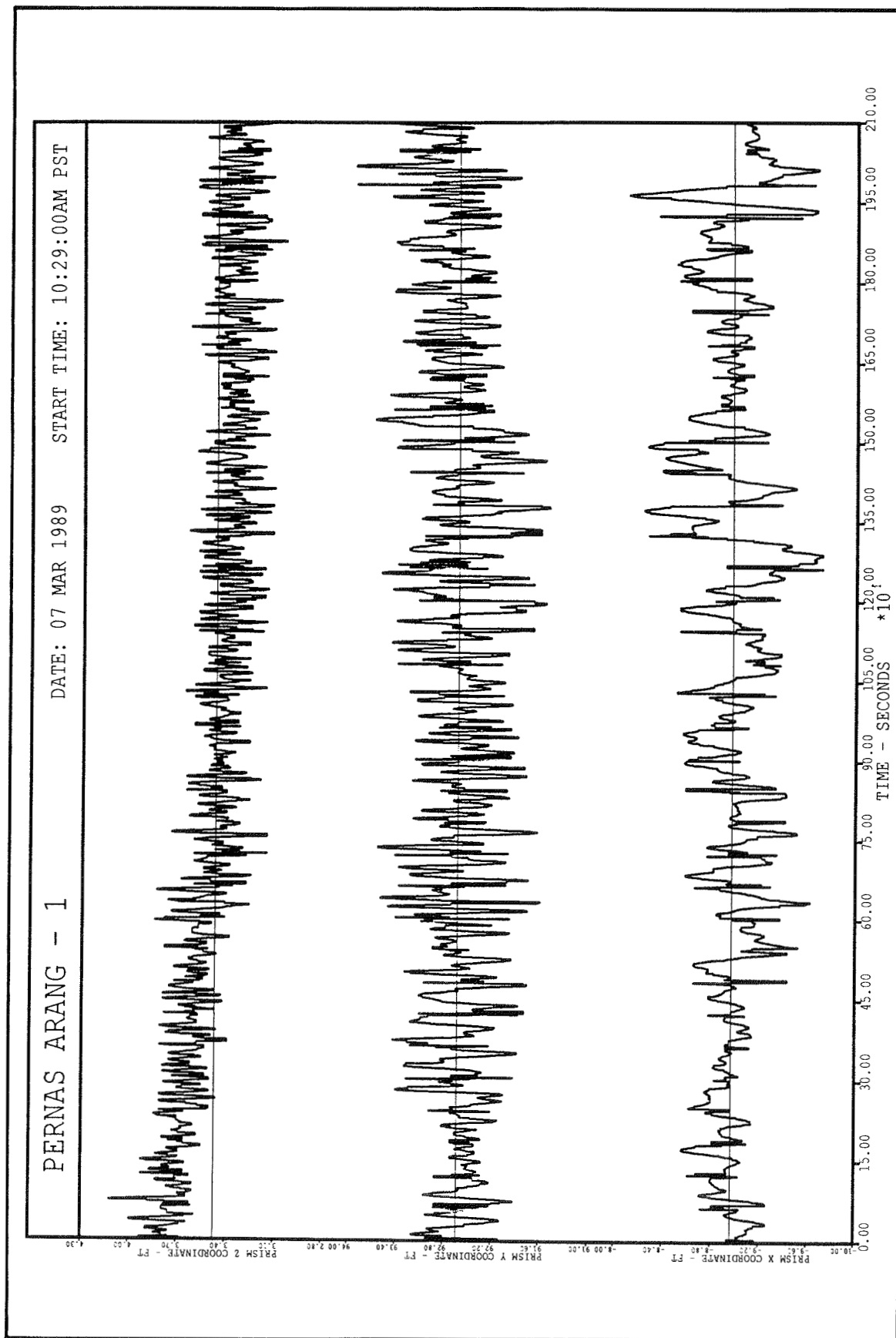
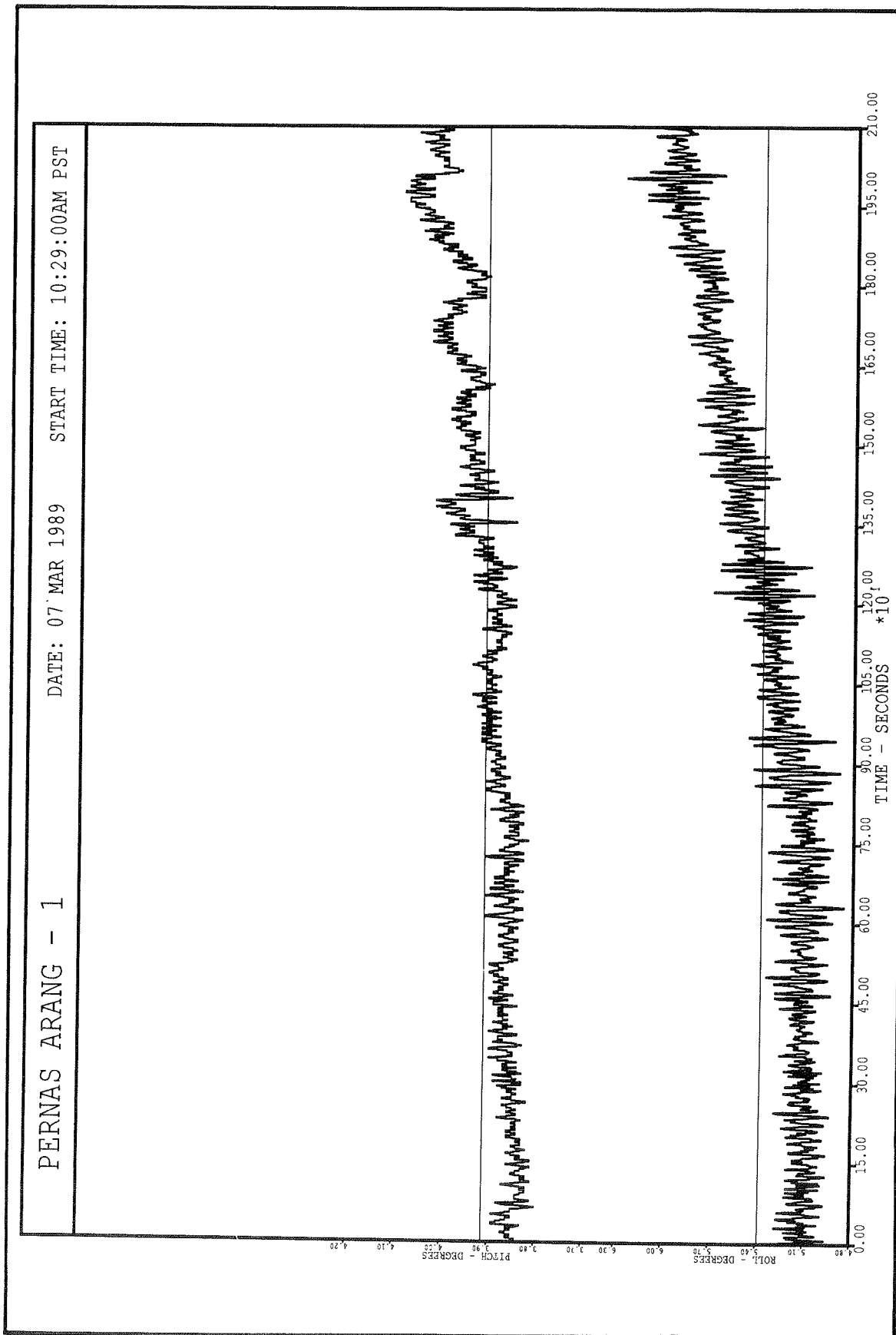
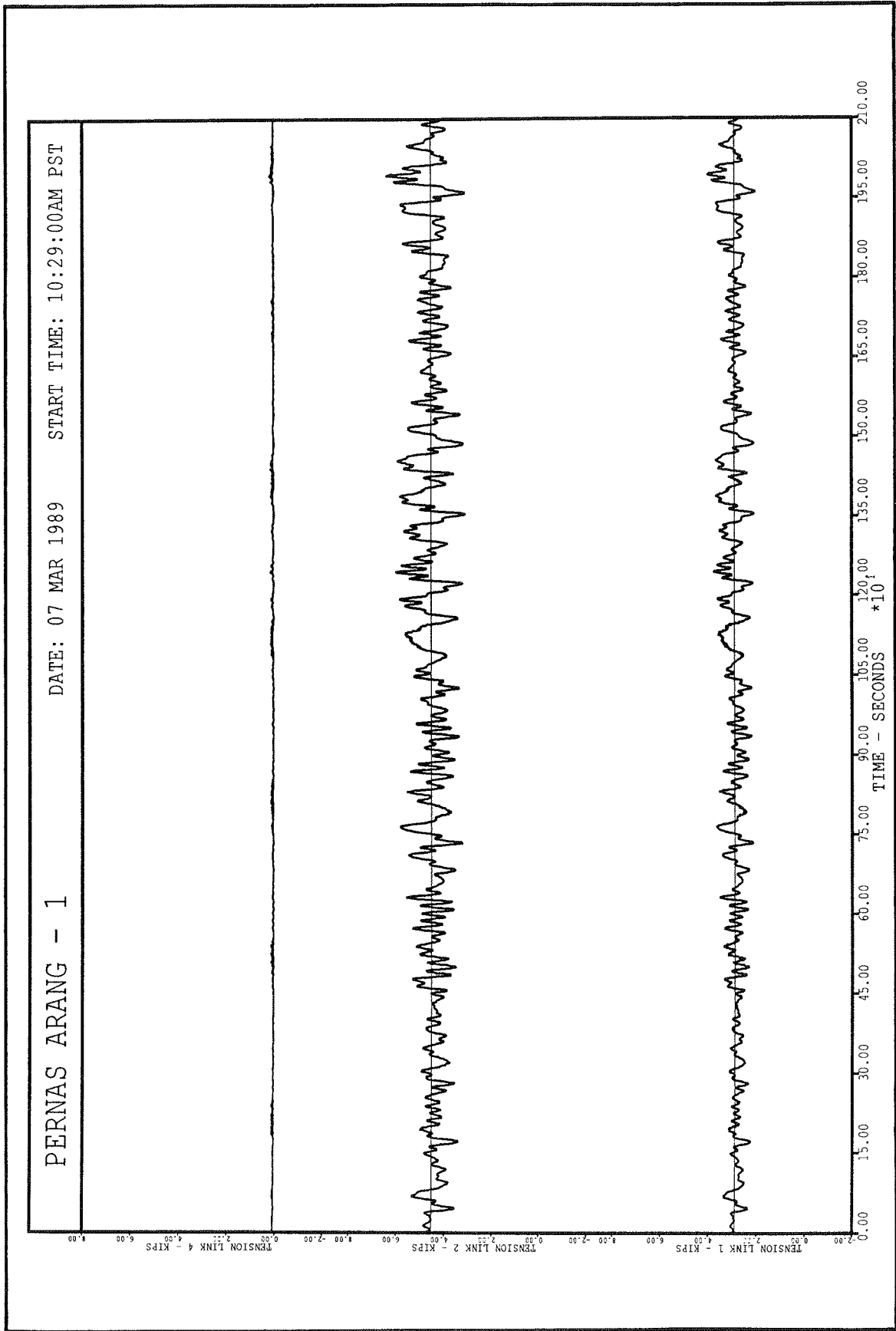
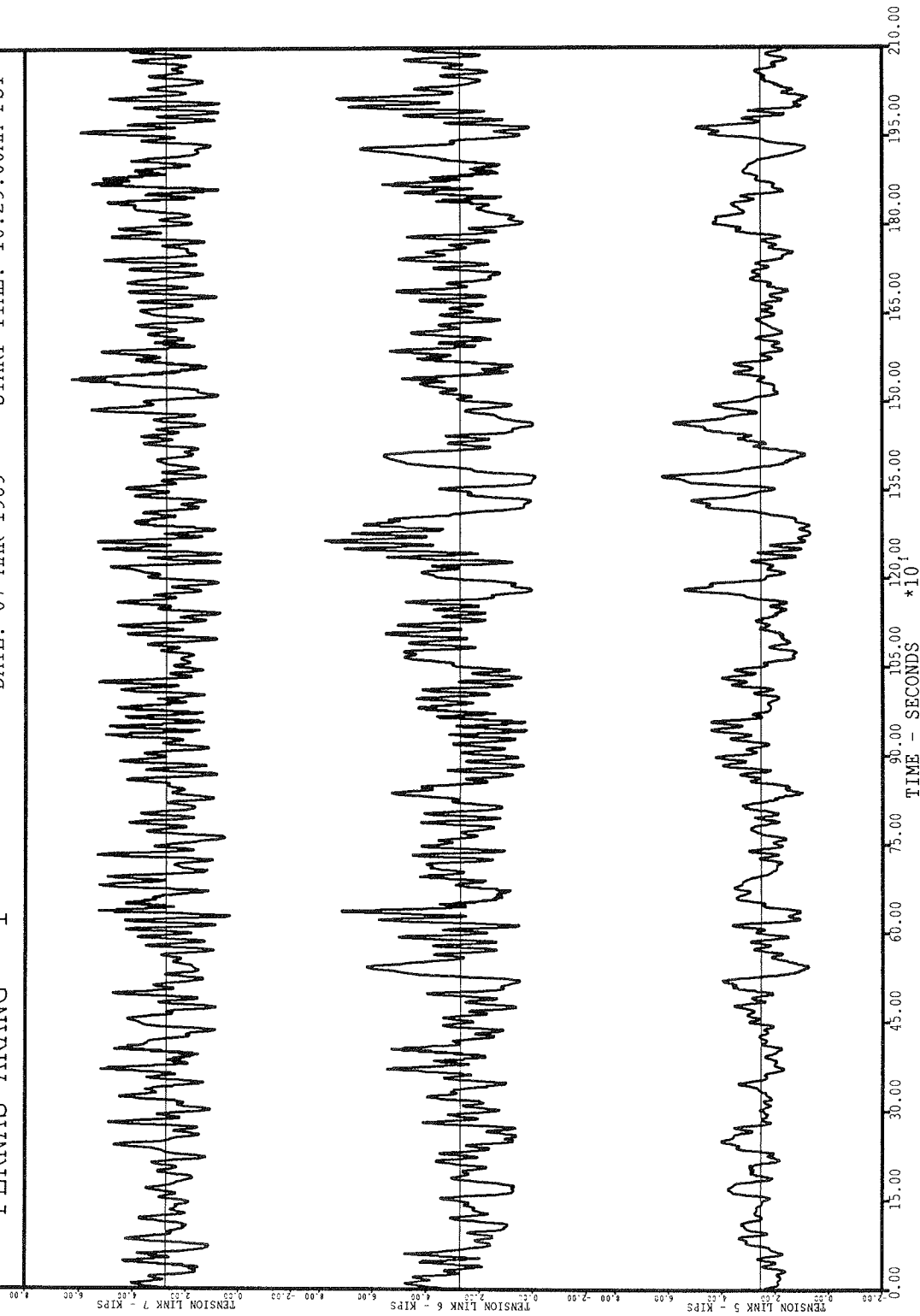


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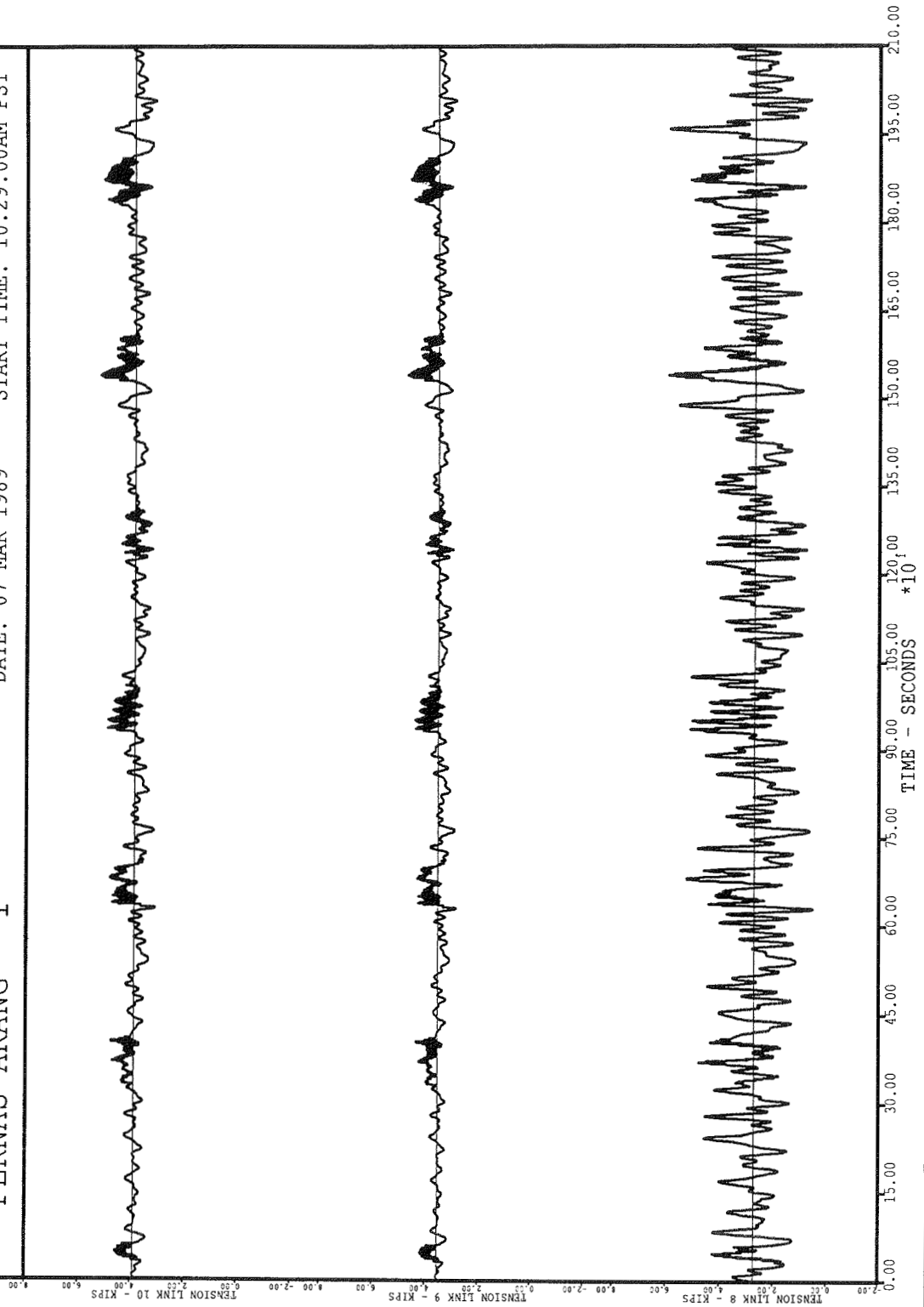


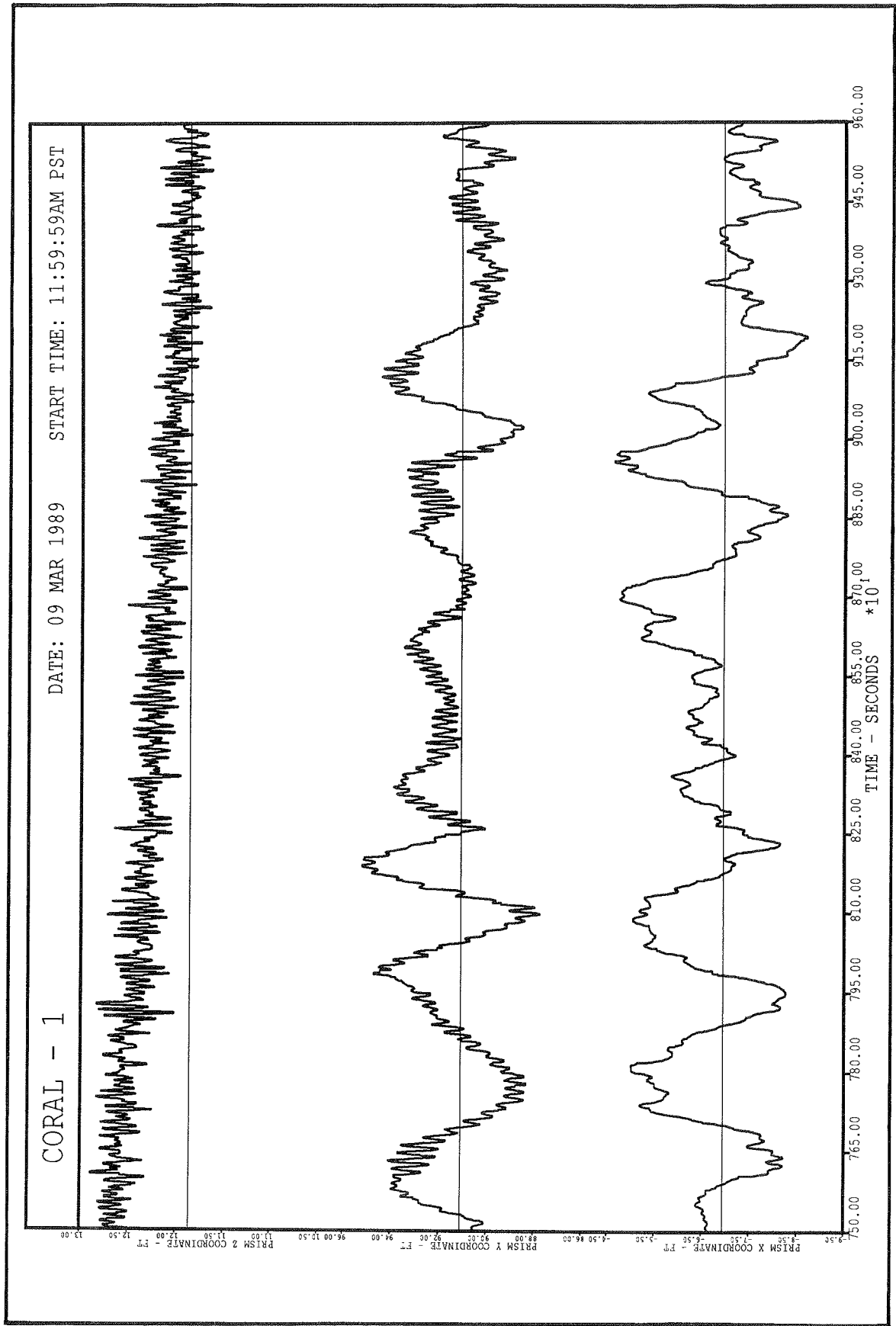


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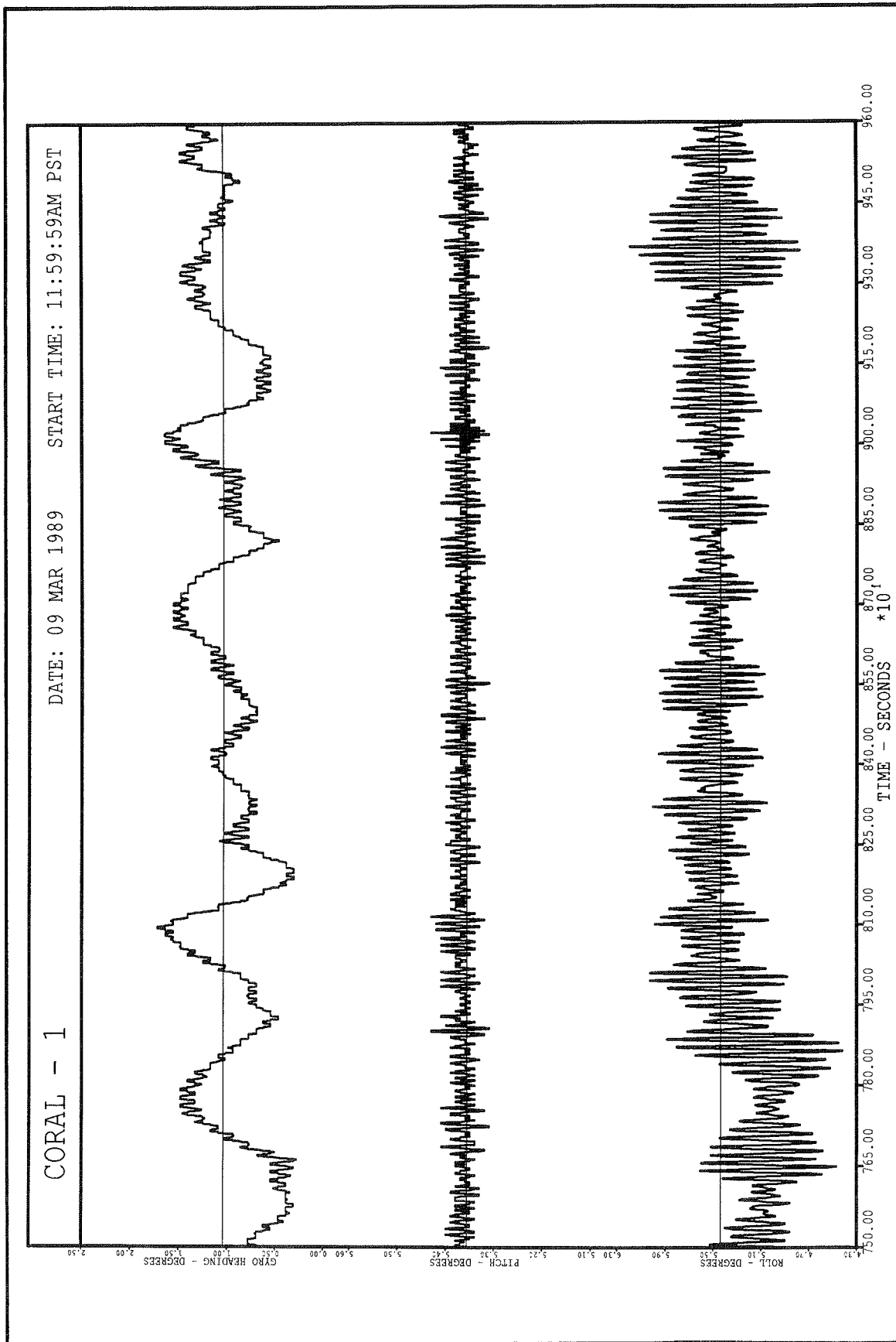
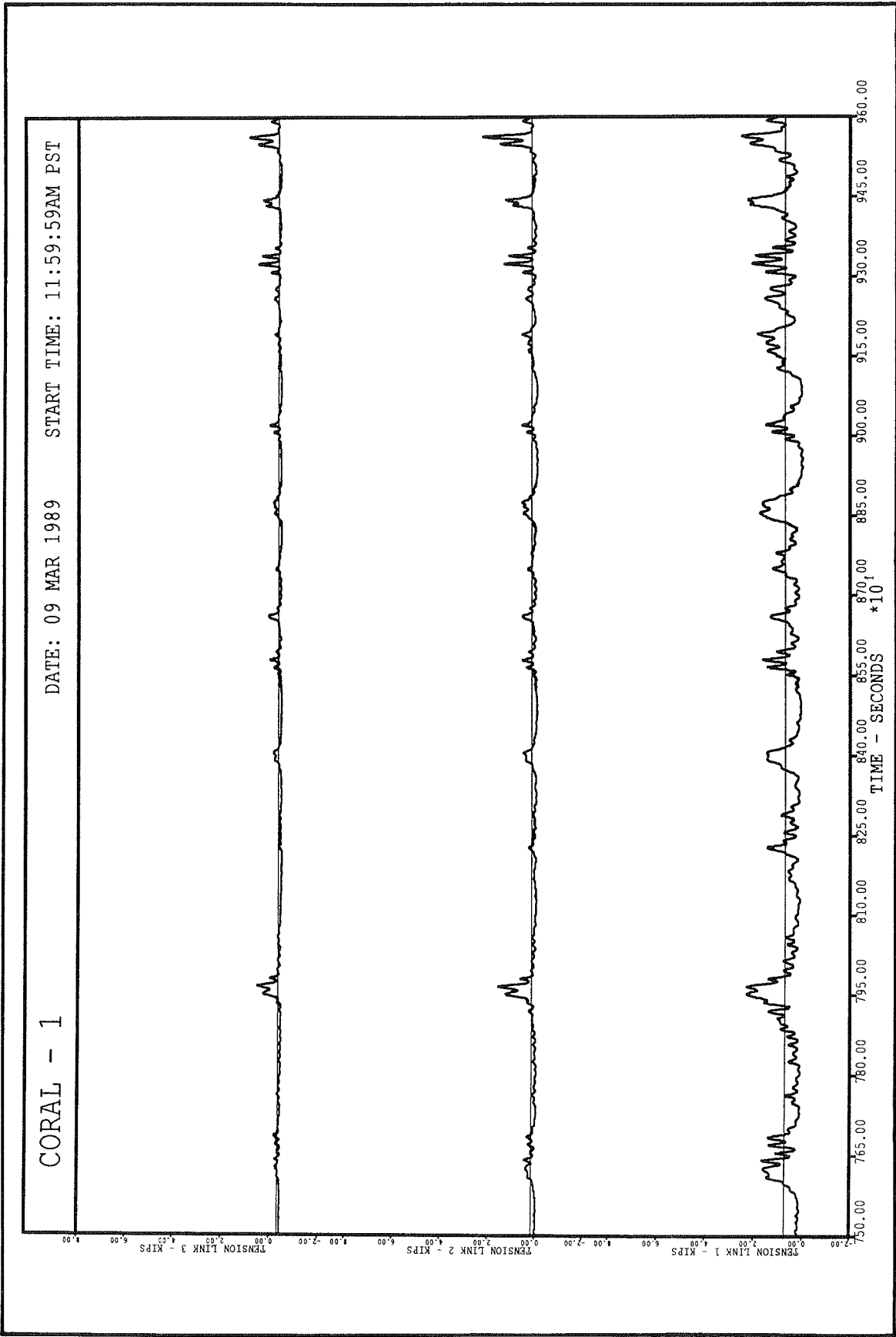
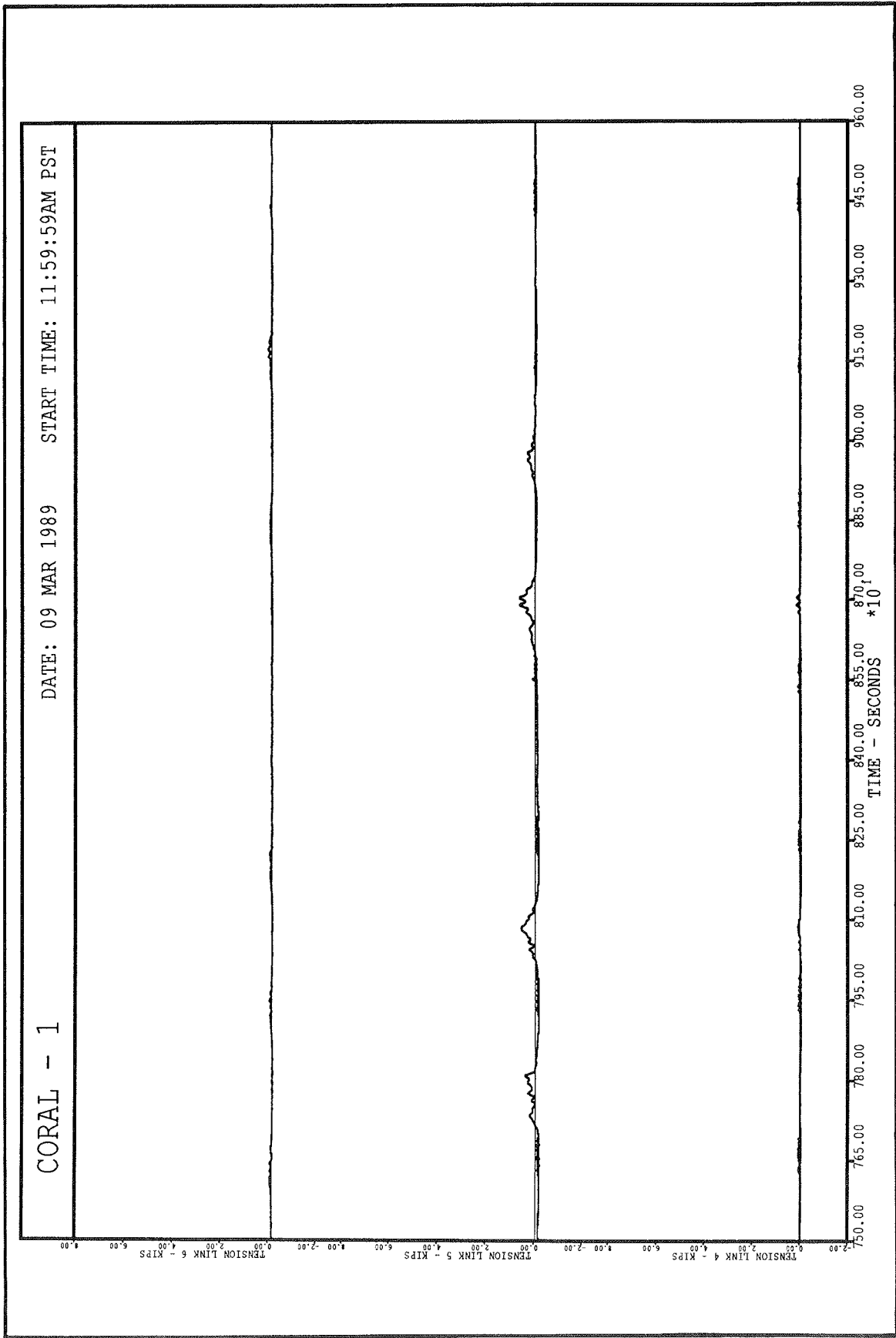
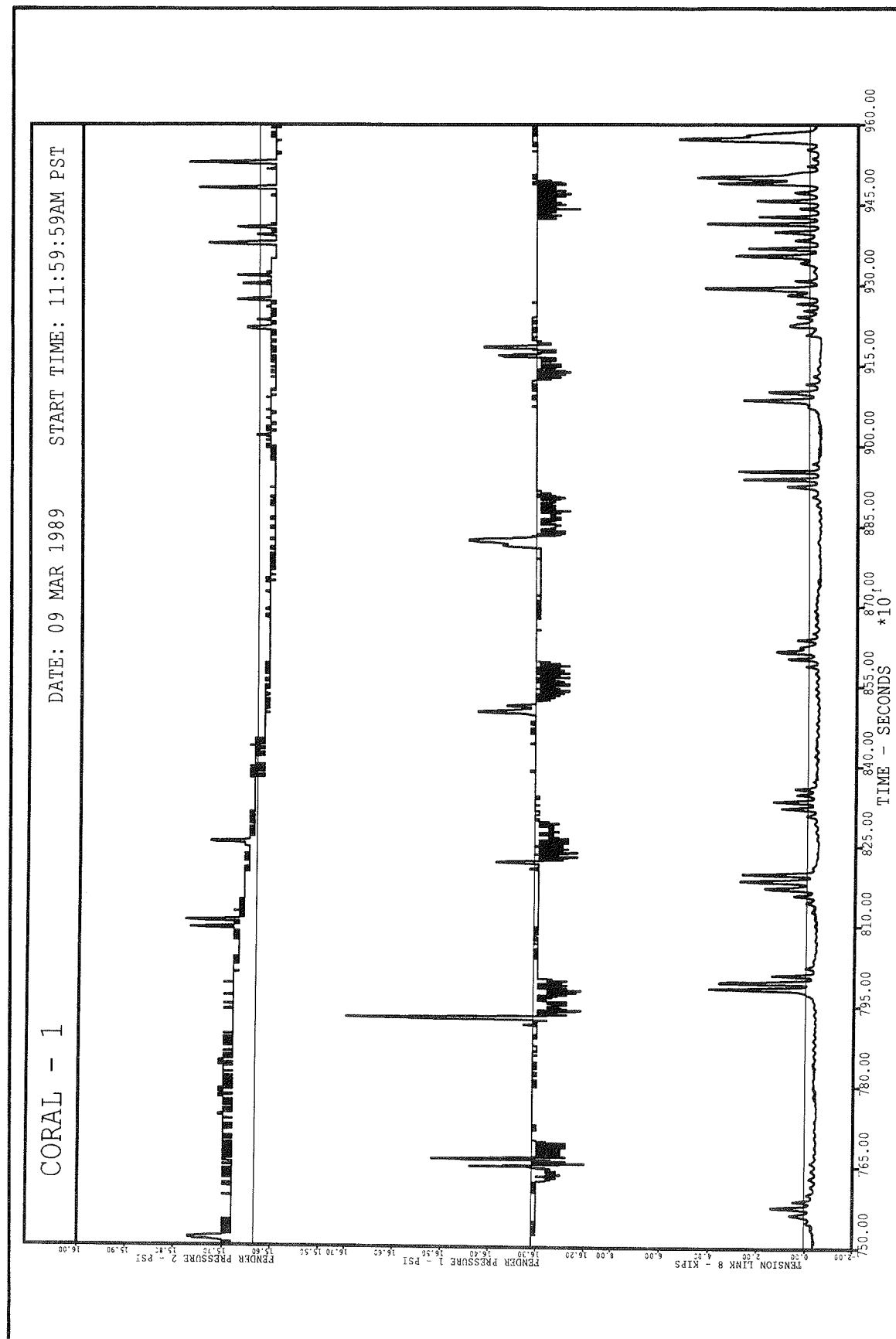
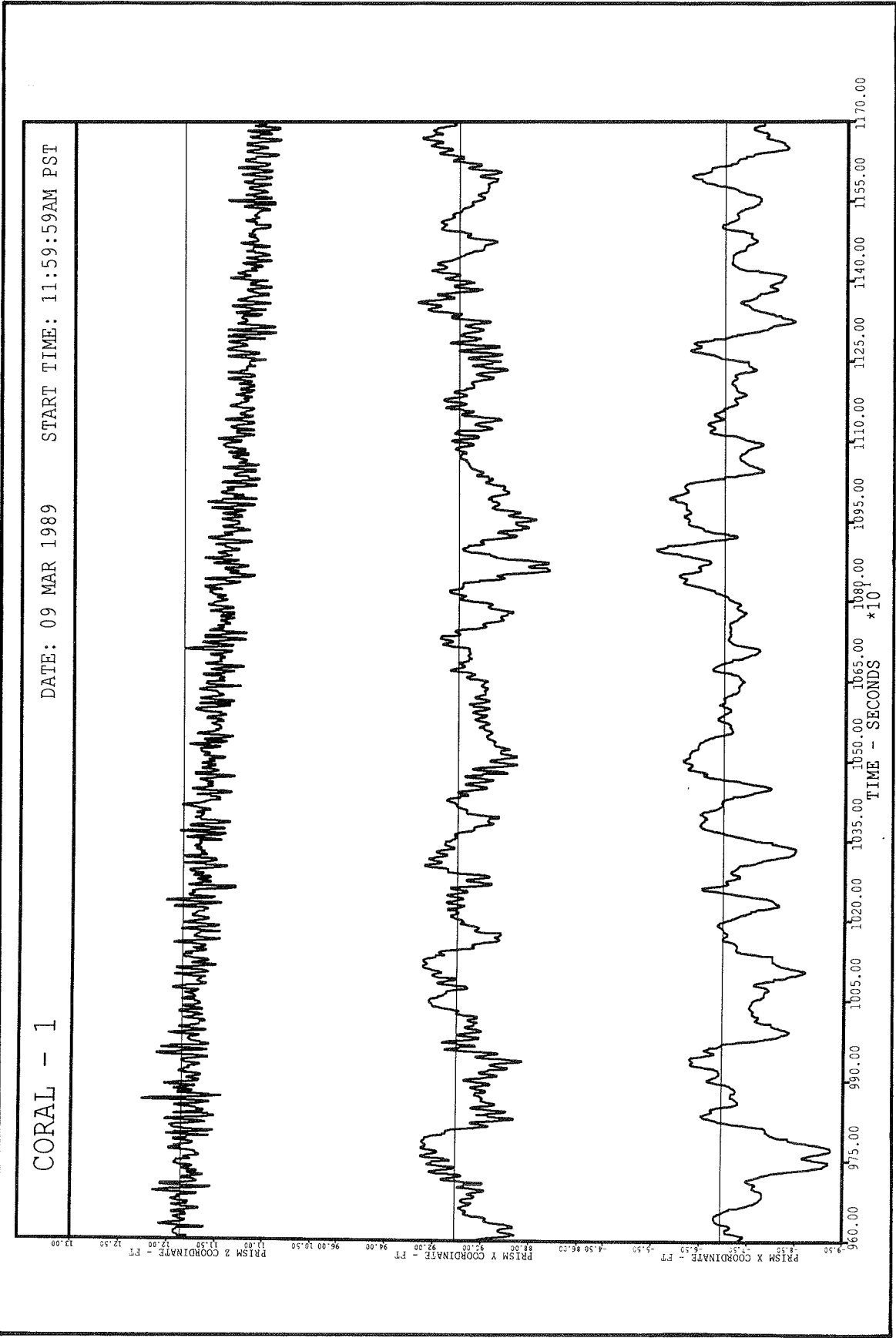


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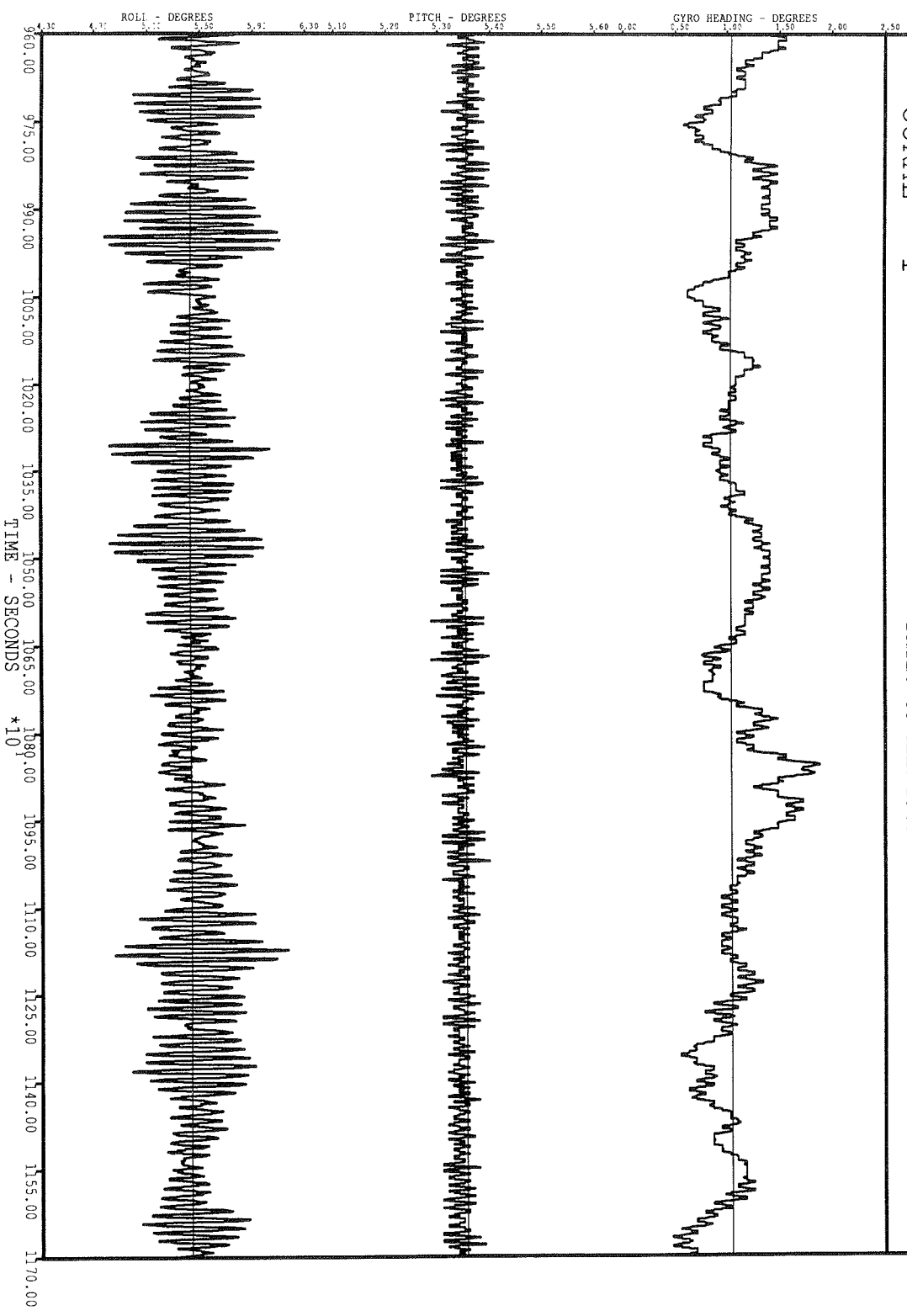


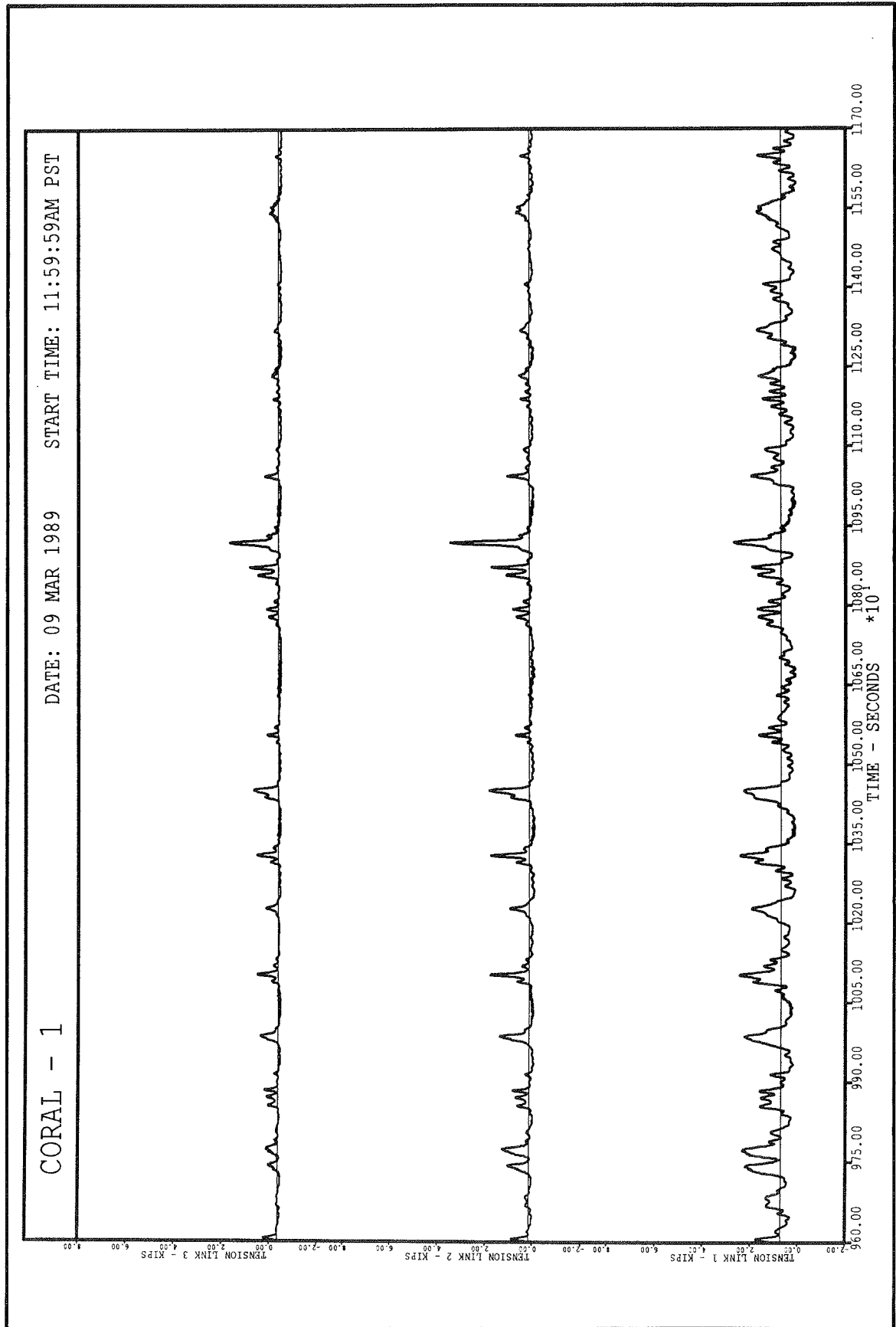


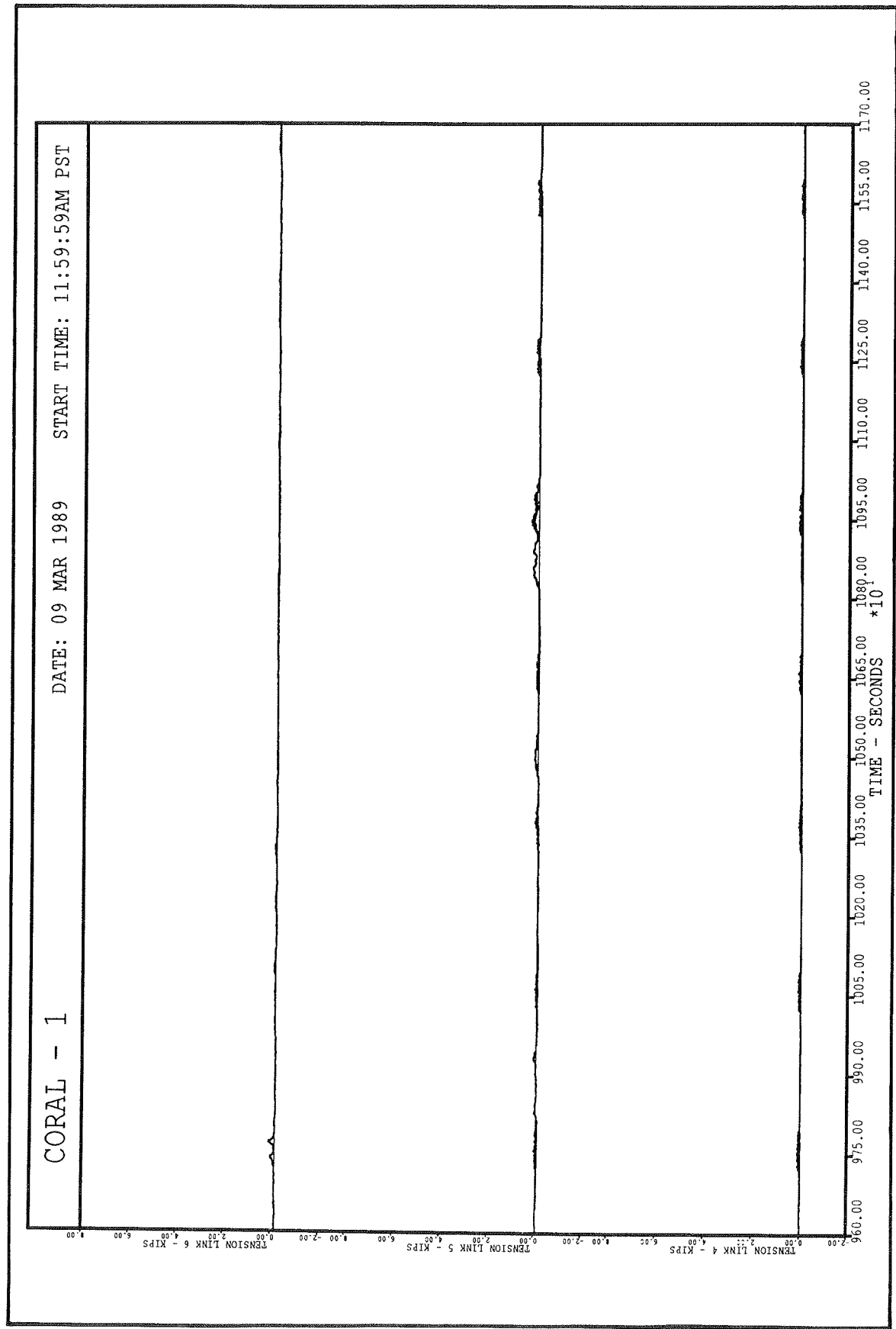
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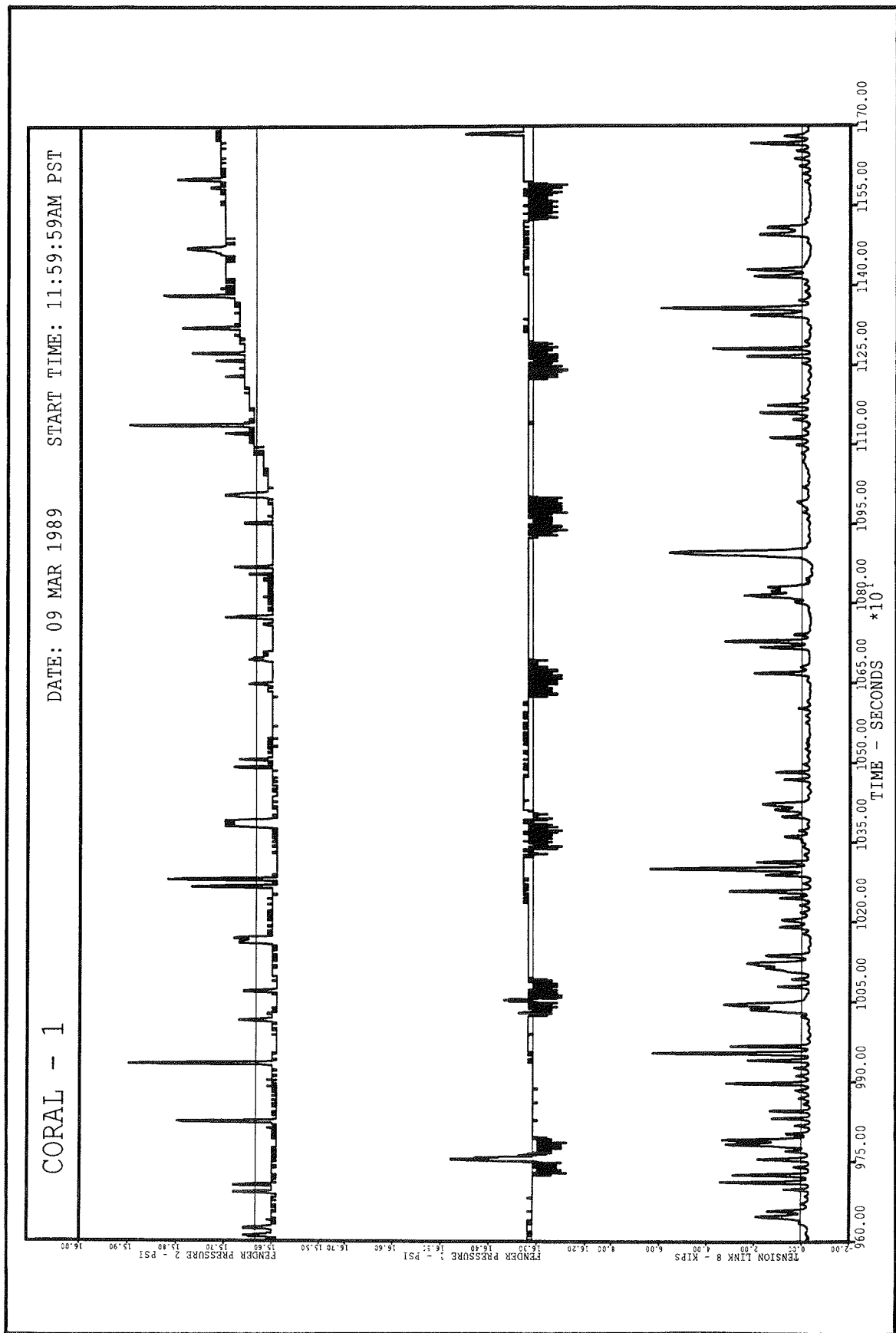
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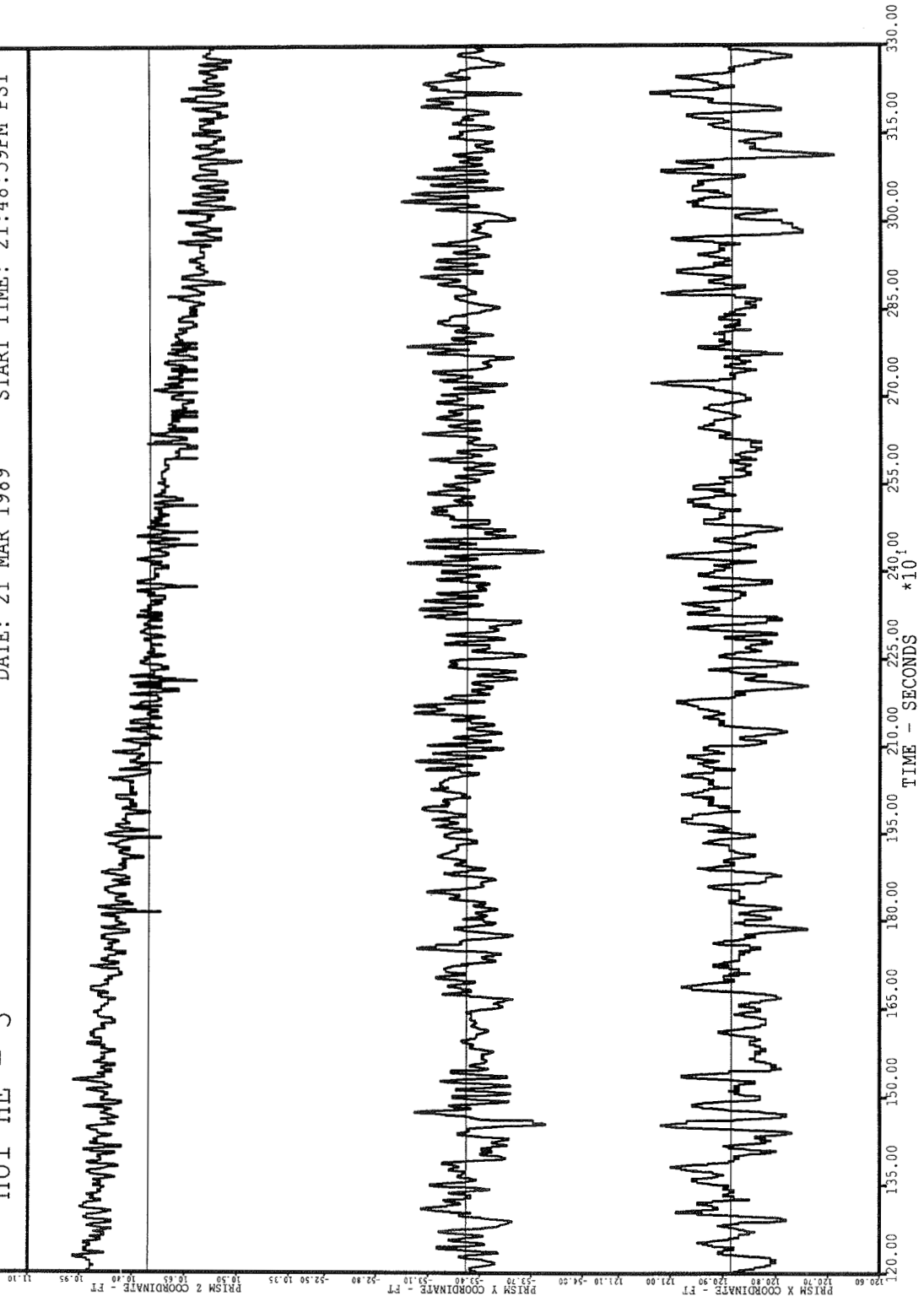


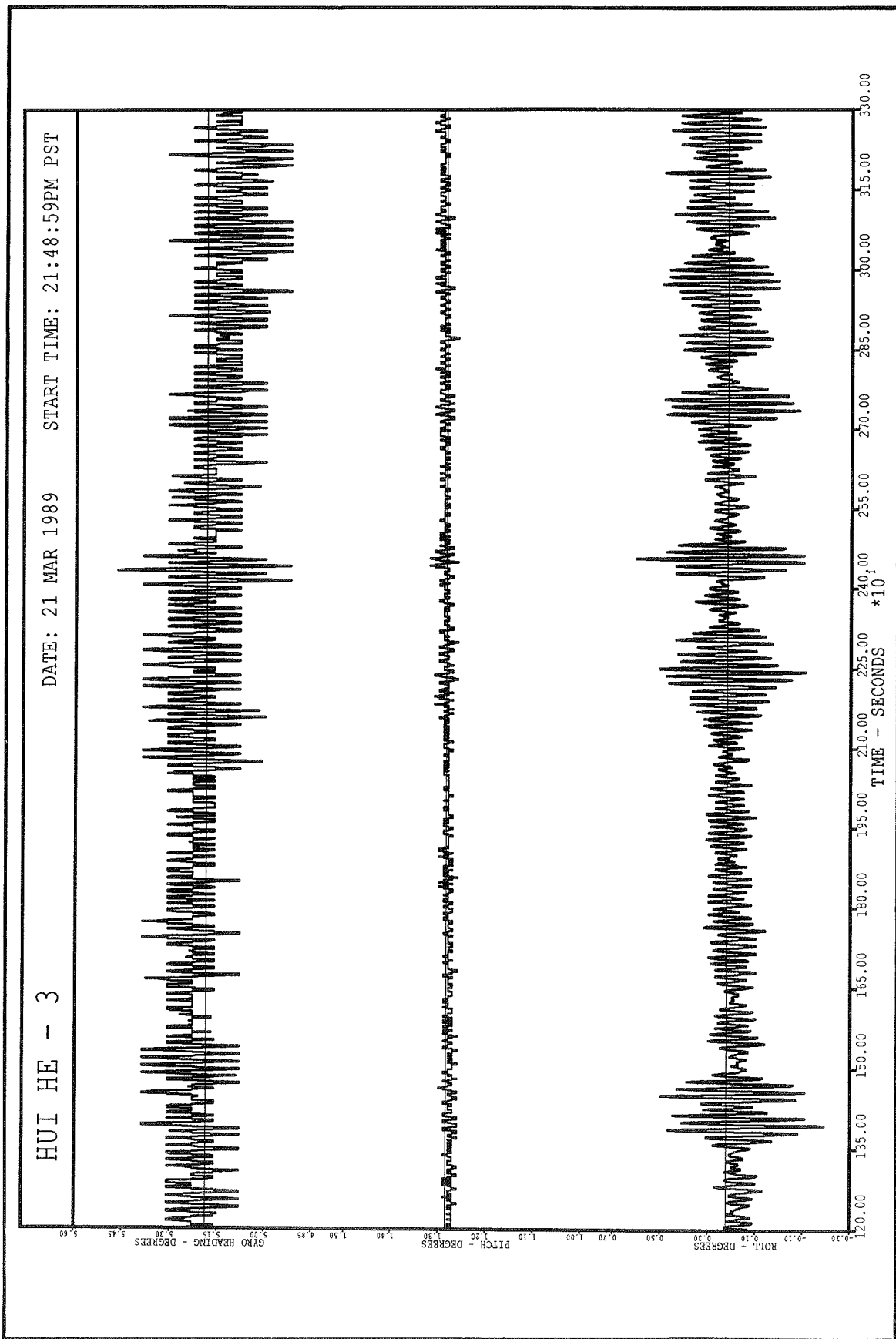






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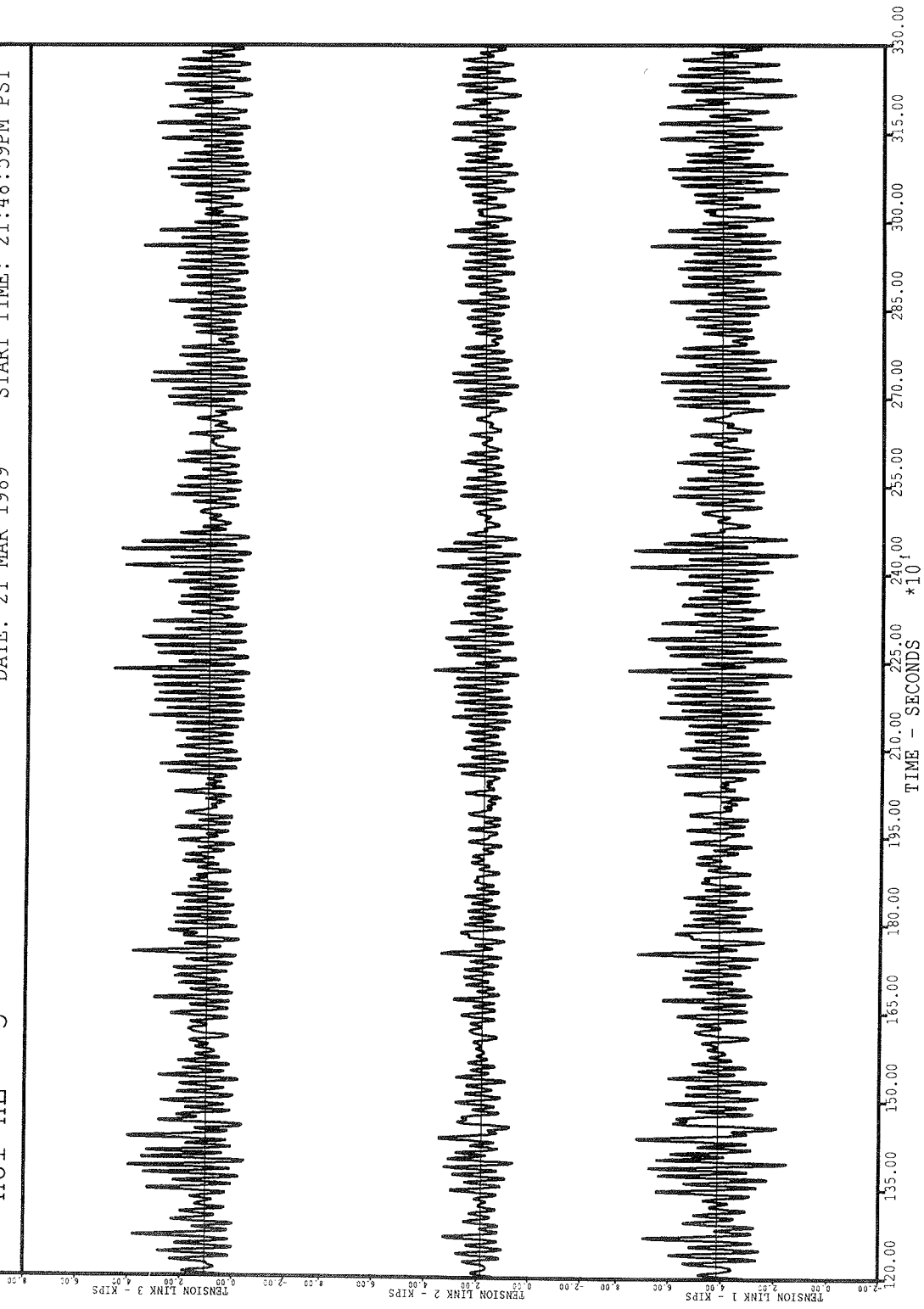




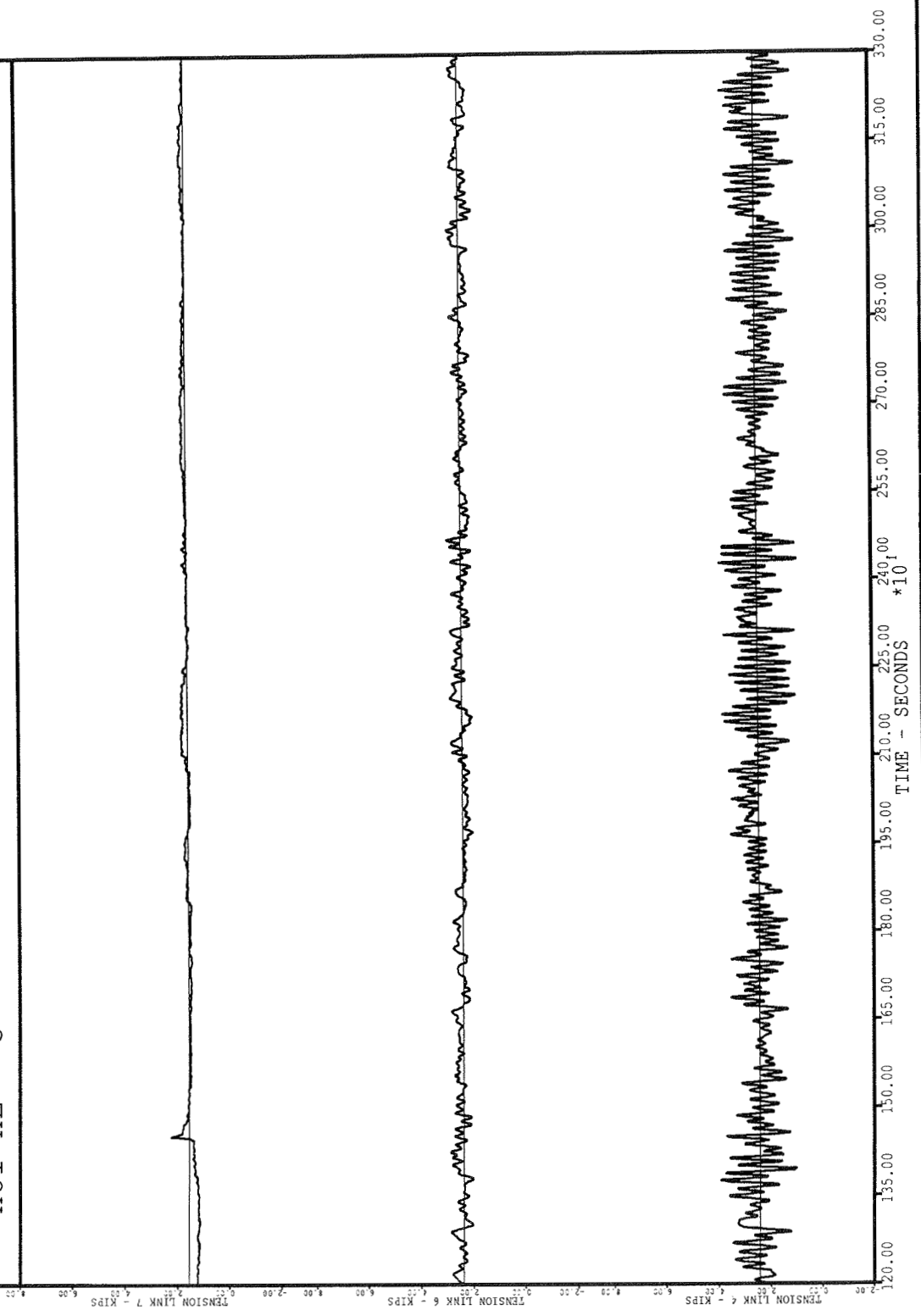
HUI HE - 3

DATE: 21 MAR 1989

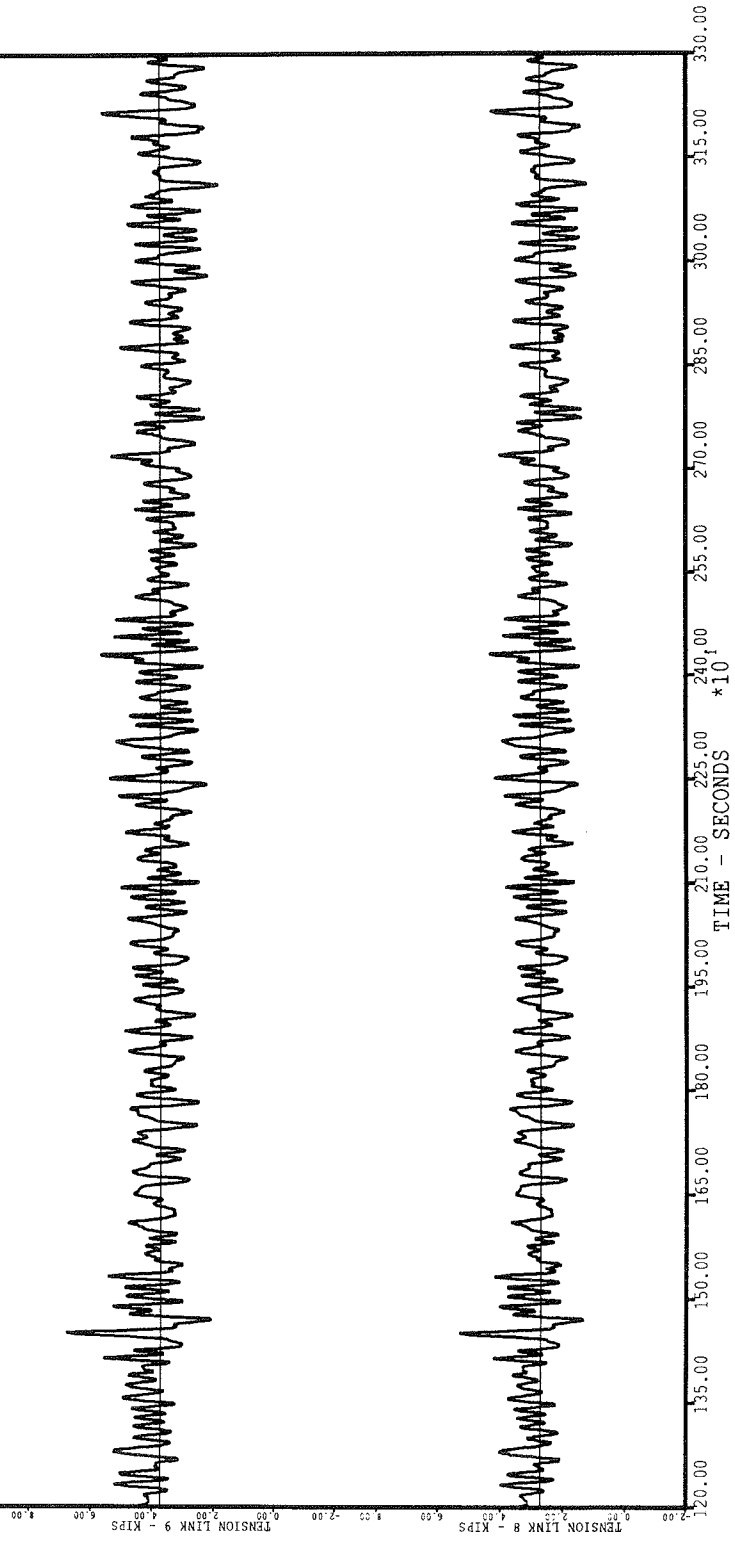
START TIME: 21:48:59PM PST



HUI HE - 3 DATE: 21 MAR 1989 START TIME: 21:48:59PM PST



HUI HE - 3 DATE: 21 MAR 1989 START TIME: 21:48:59PM PST



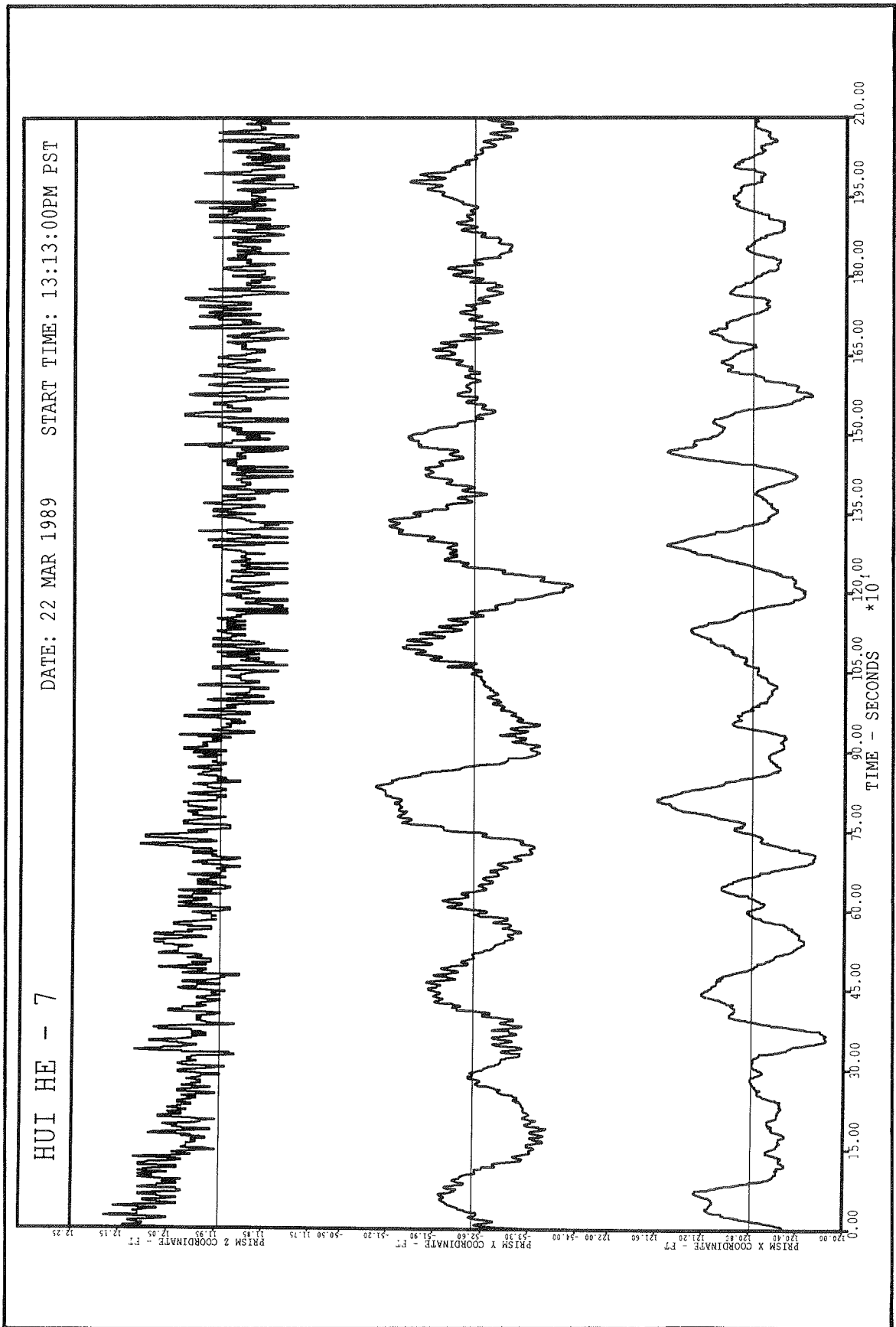
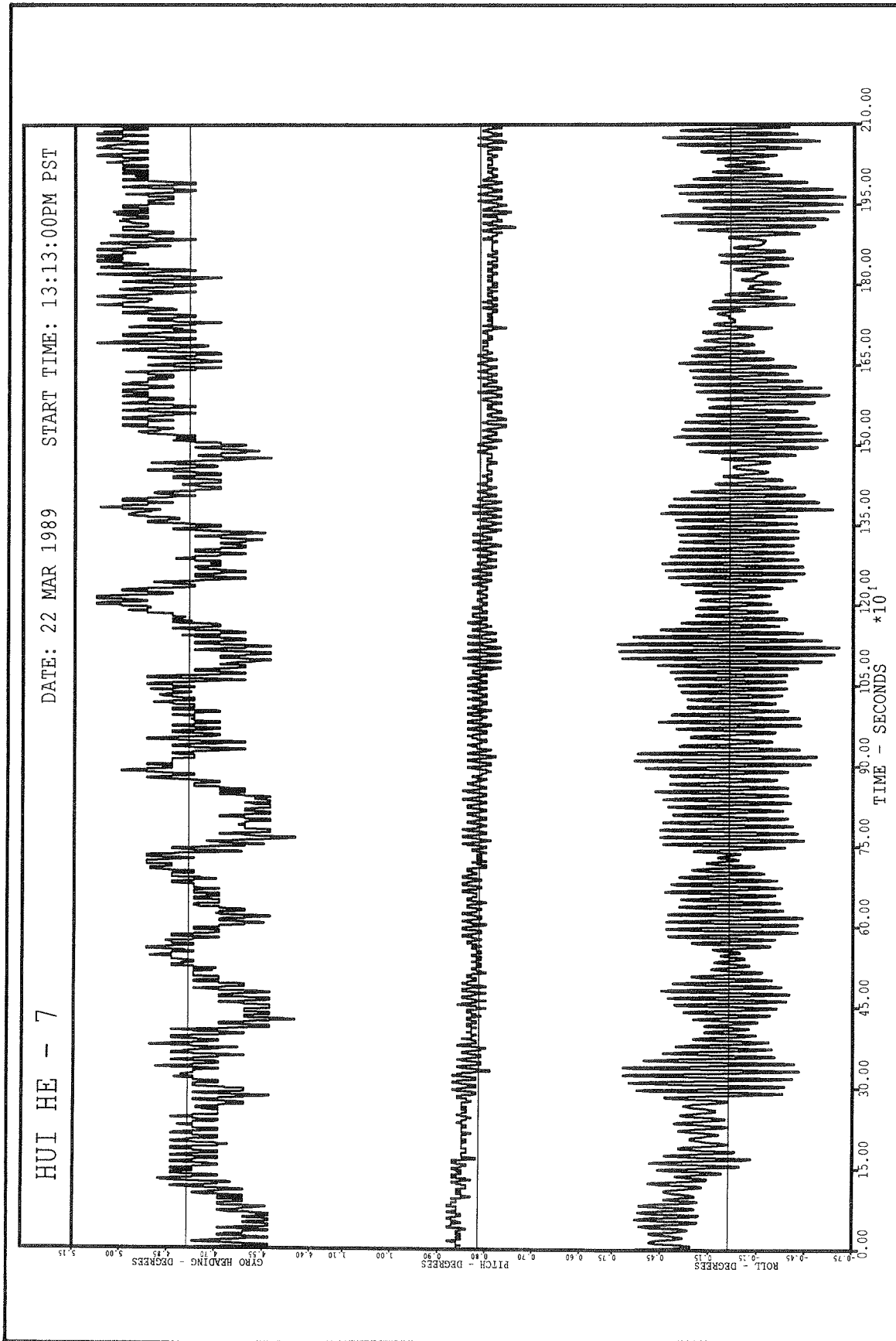


PLATE 56



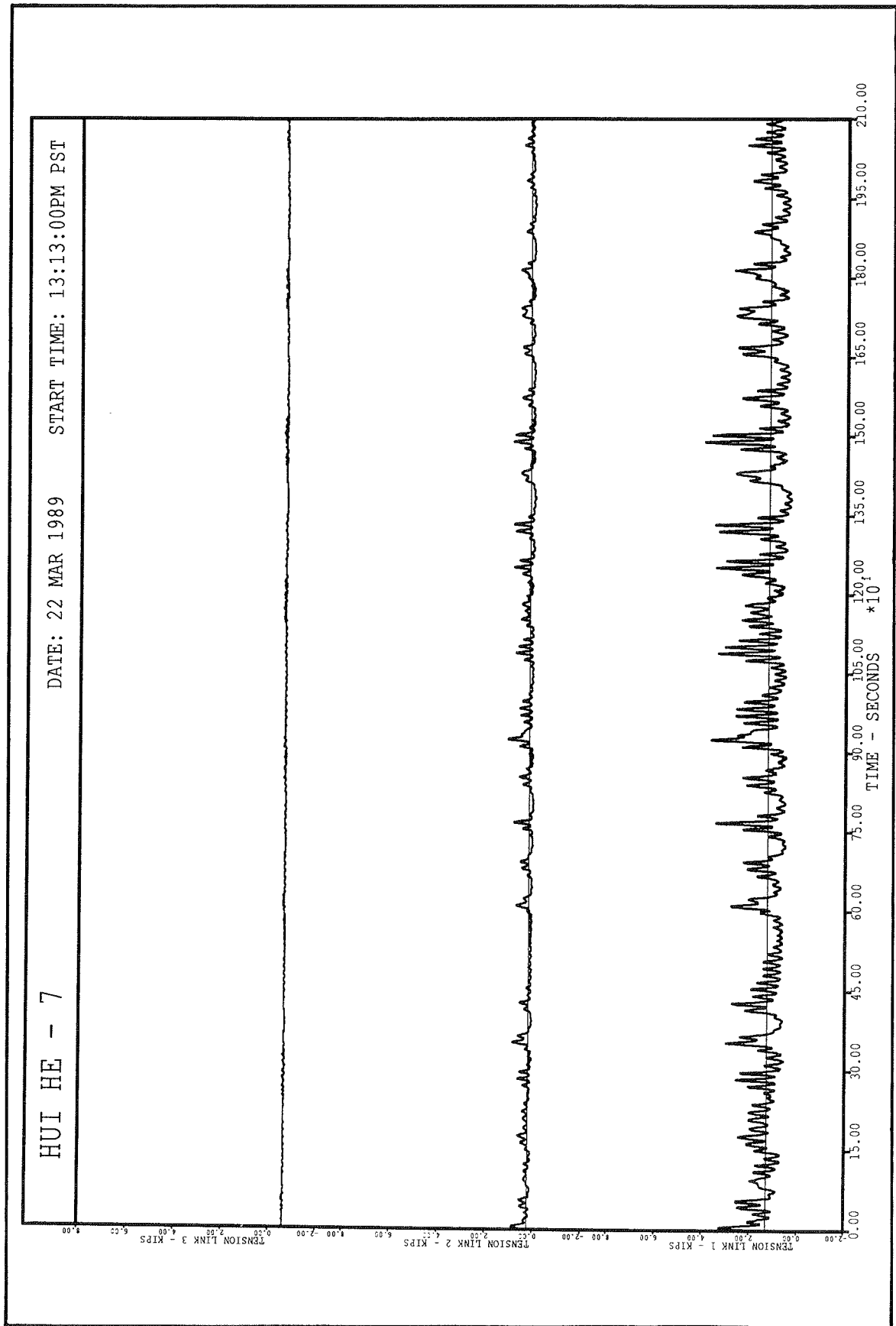
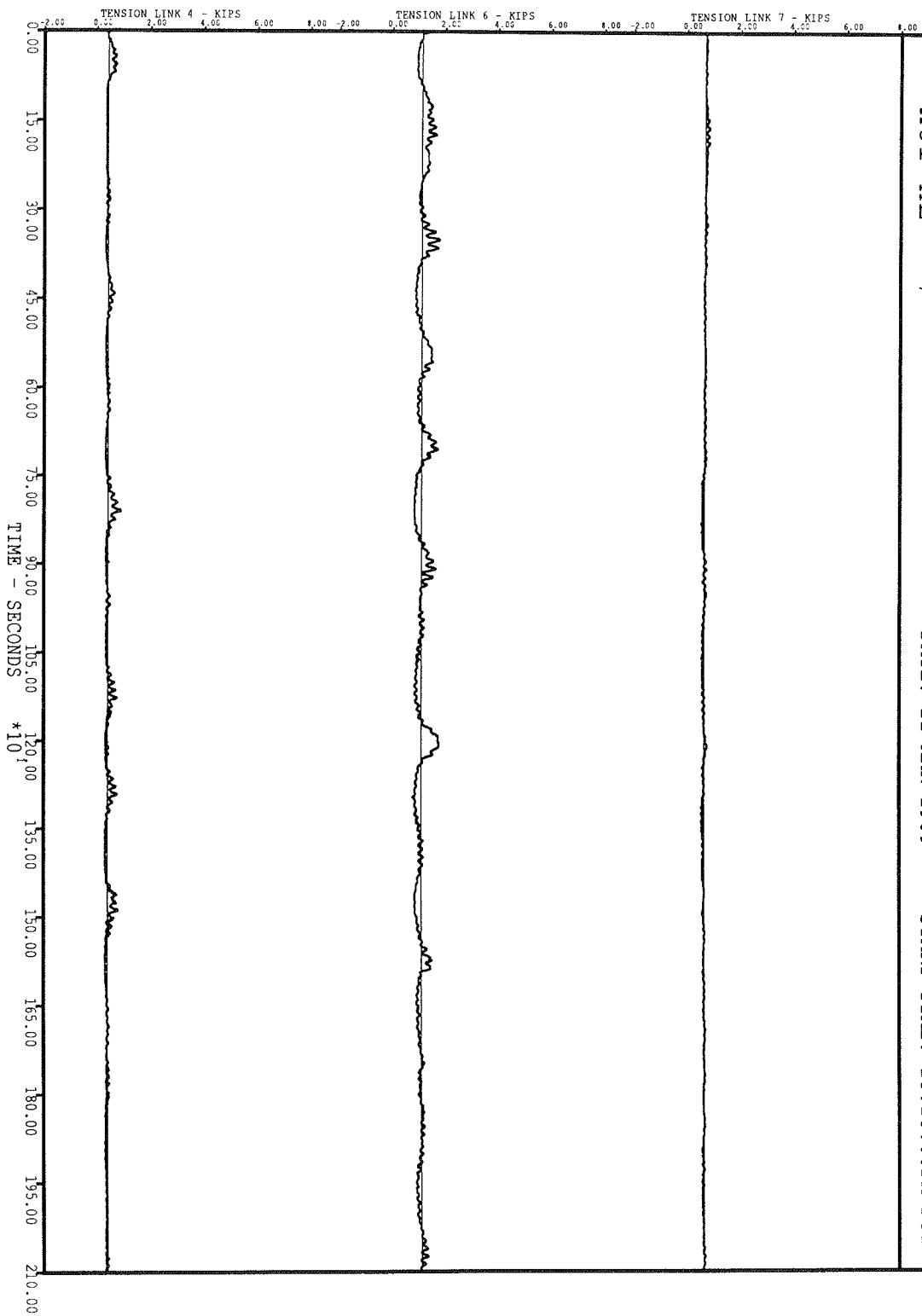


PLATE 58

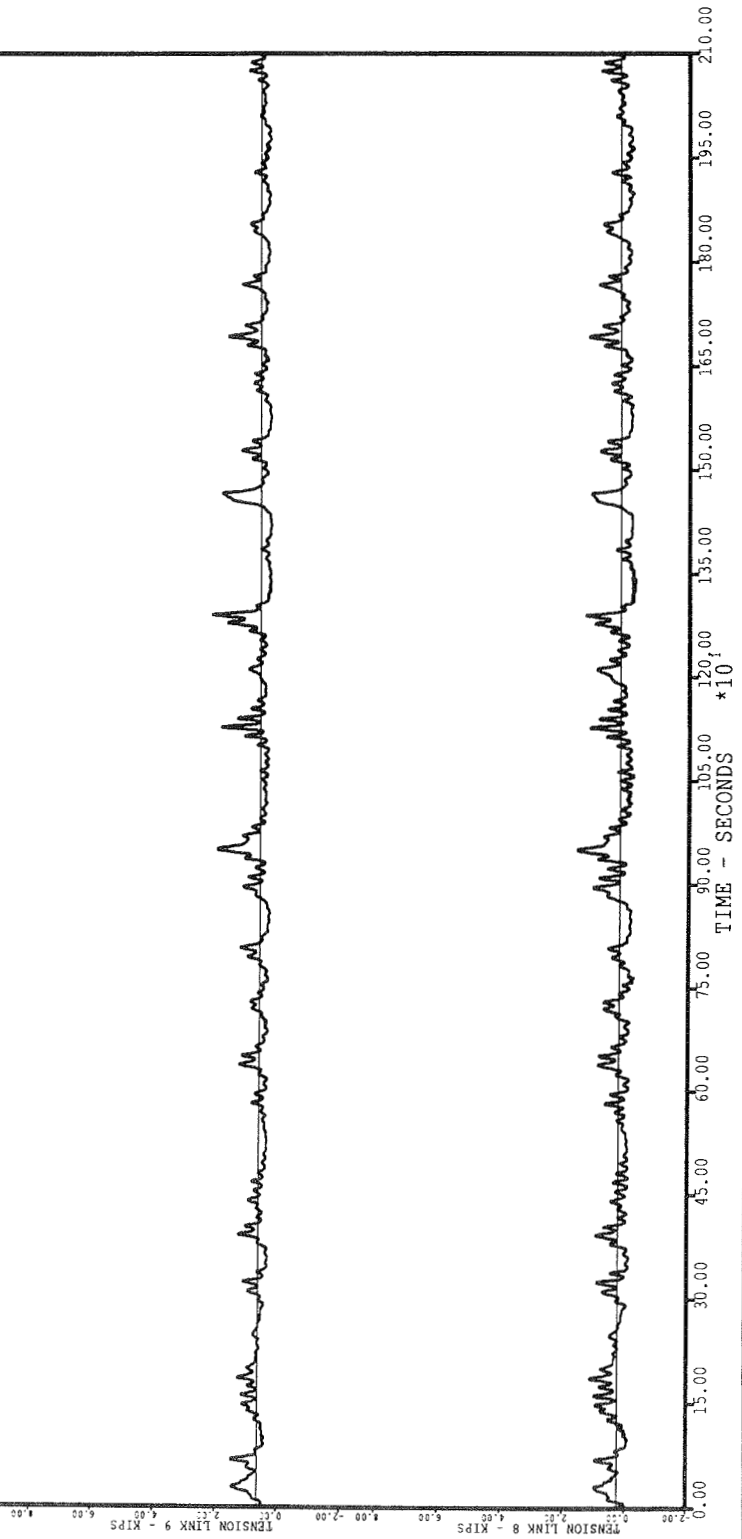
HUI HE - 7

DATE: 22 MAR 1989

START TIME: 13:13:00PM PST



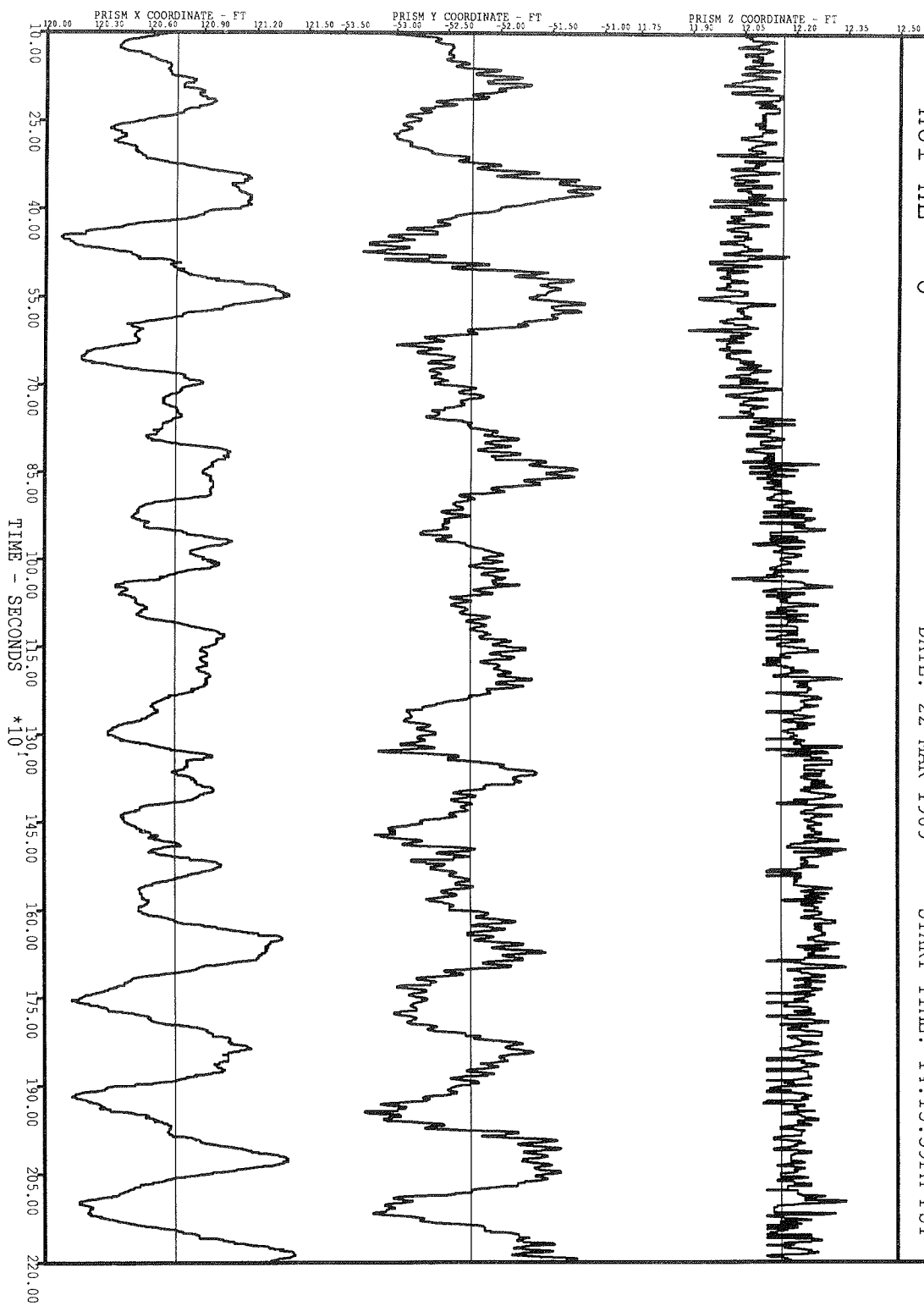
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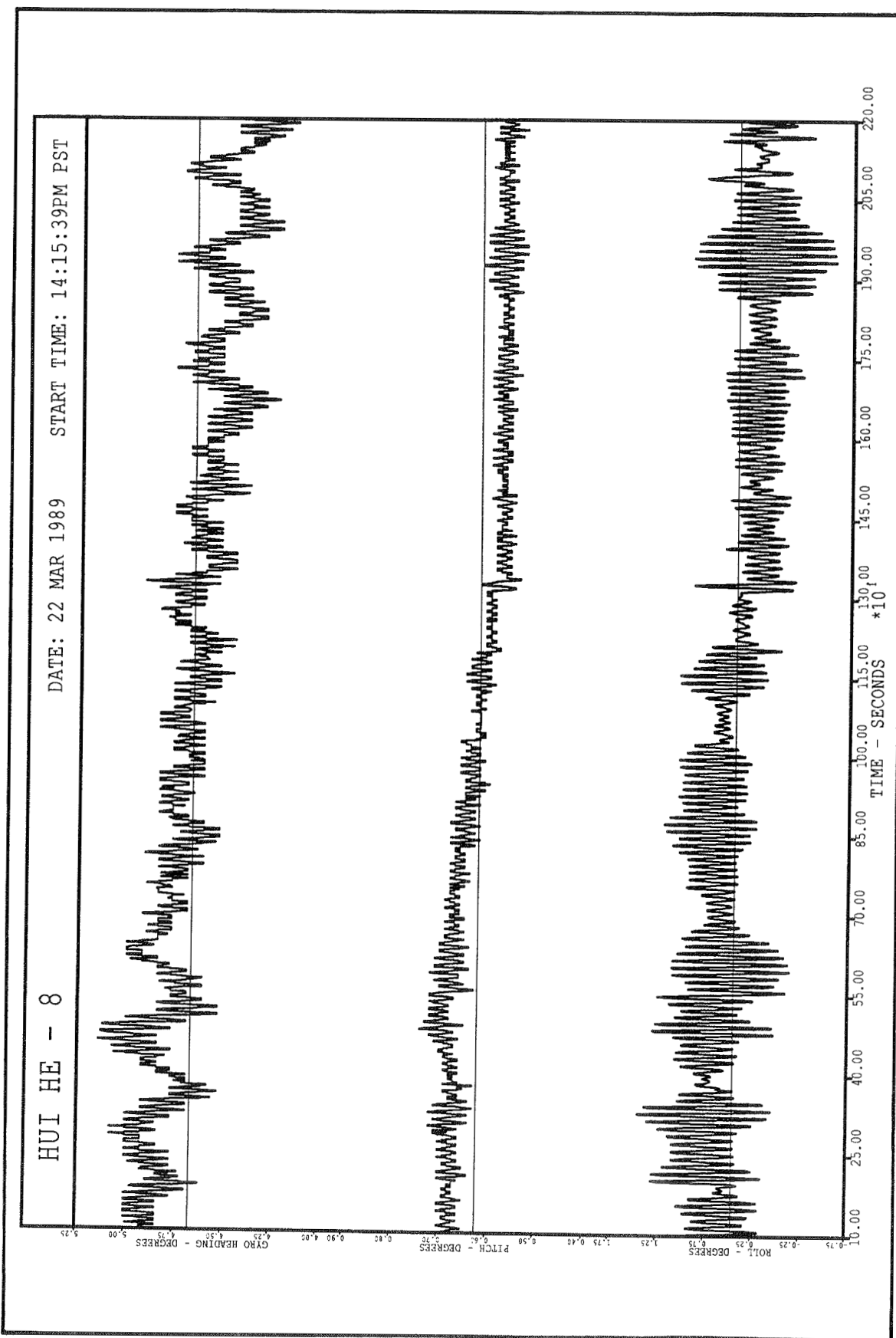


HUI HE - 8

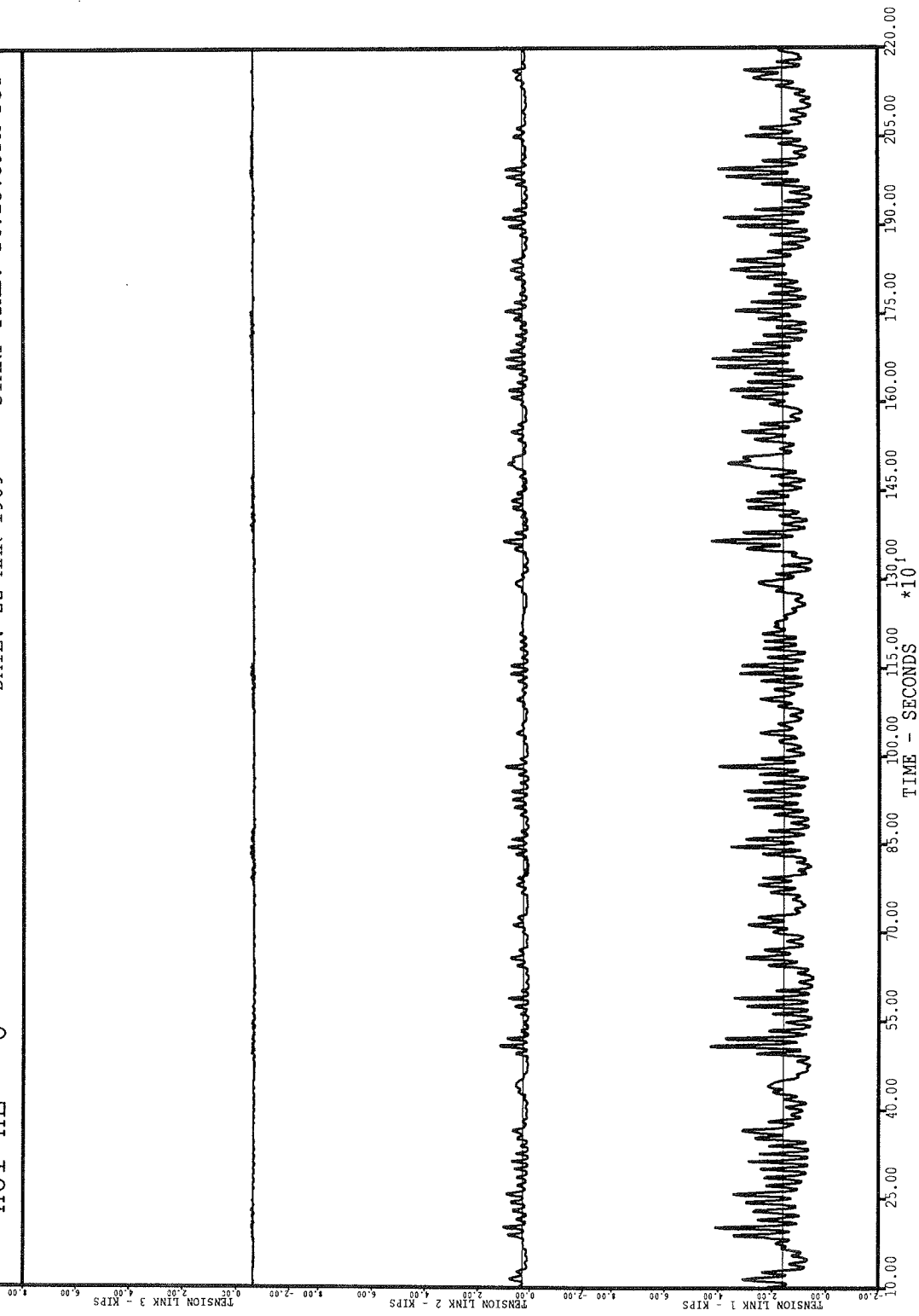
DATE: 22 MAR 1989

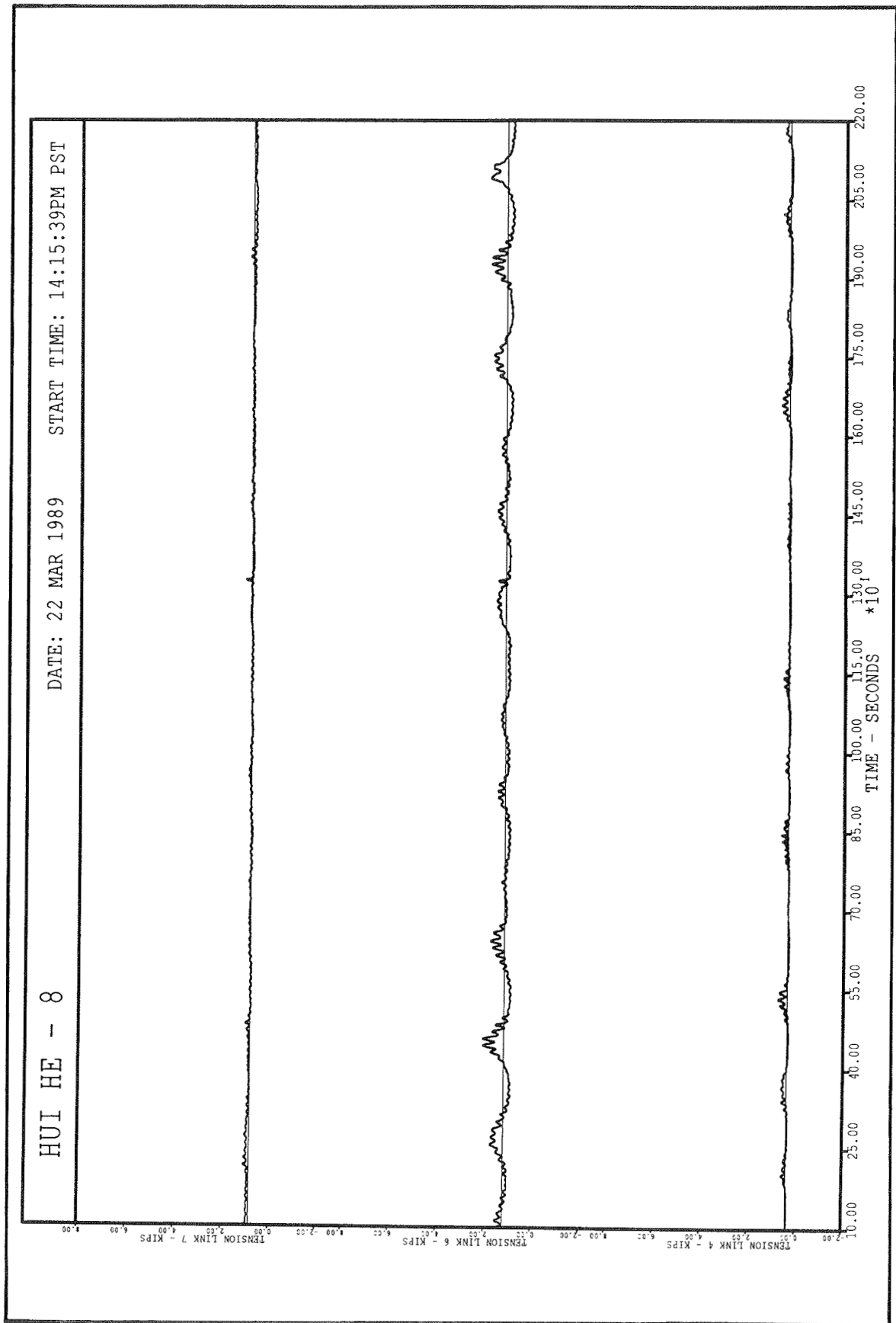
START TIME: 14:15:39PM PST



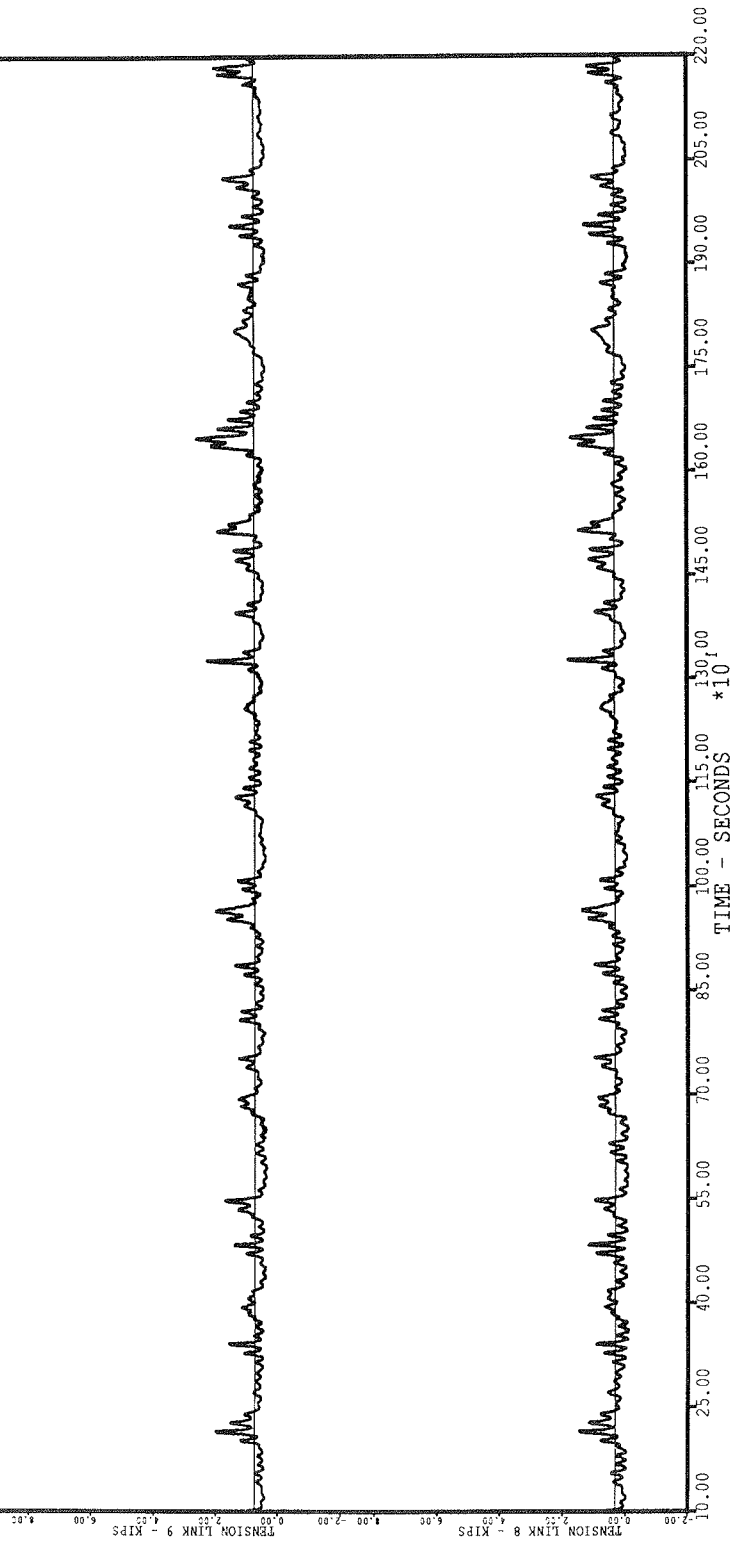


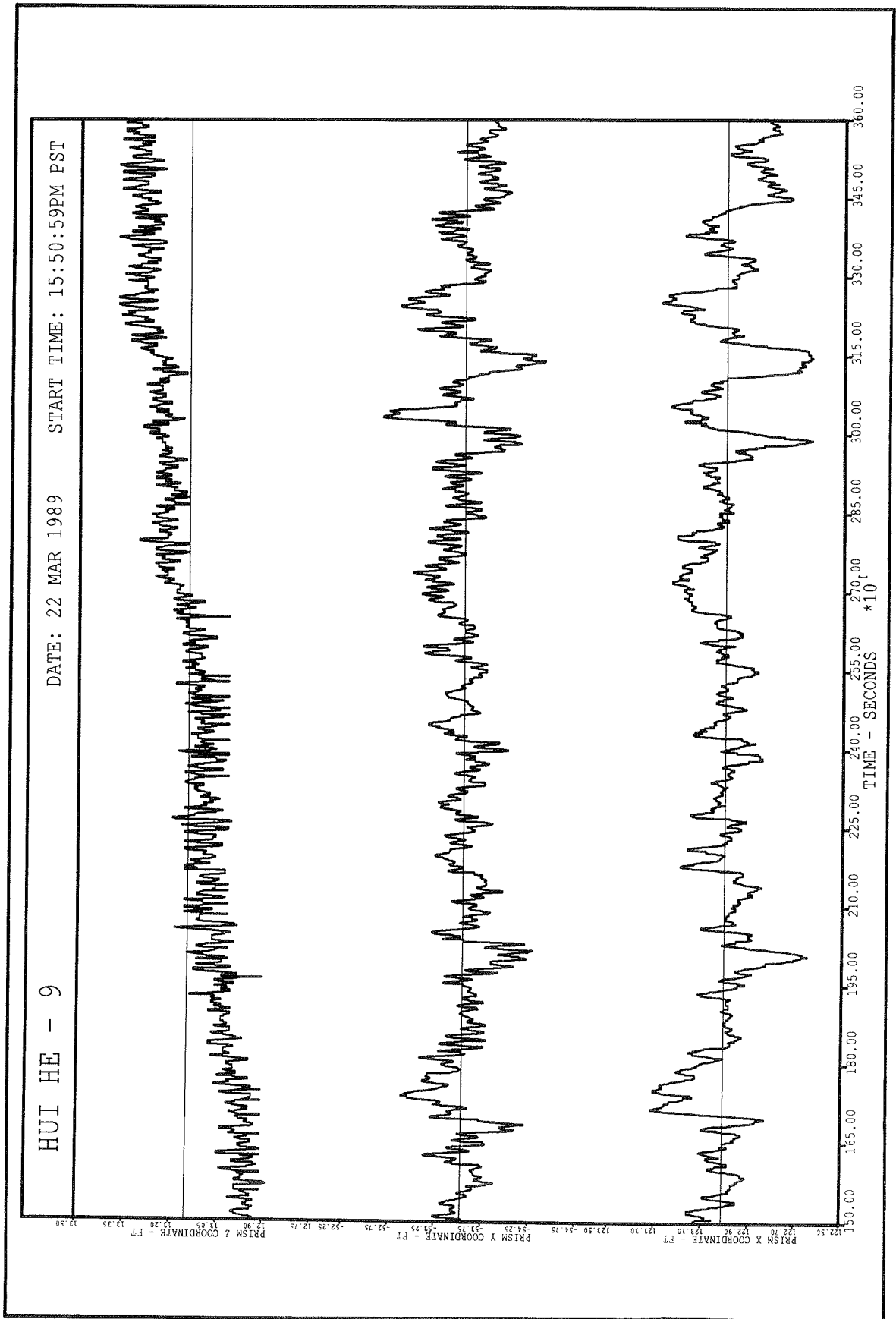
HUI HE - 8 DATE: 22 MAR 1989 START TIME: 14:15:39PM PST



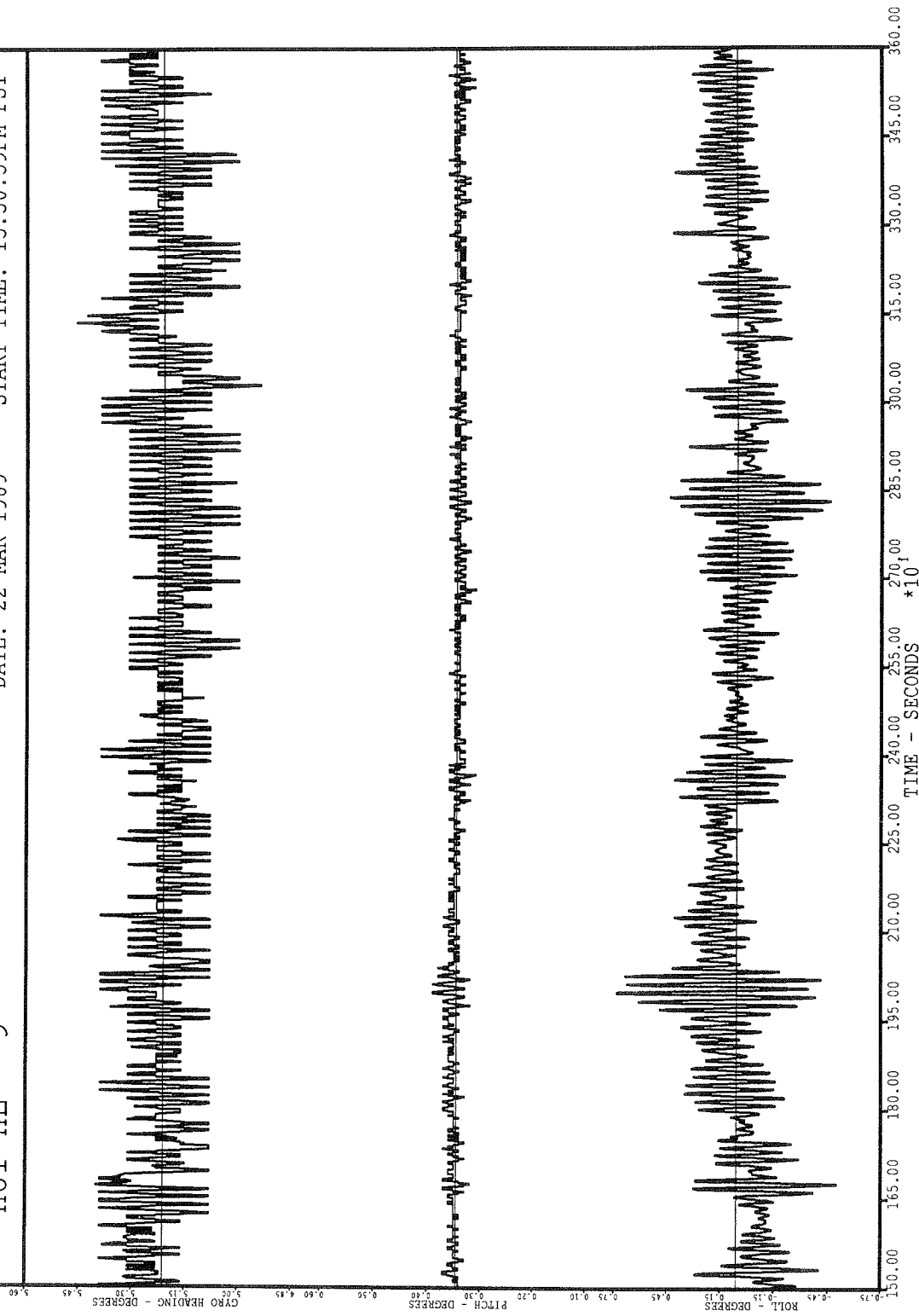


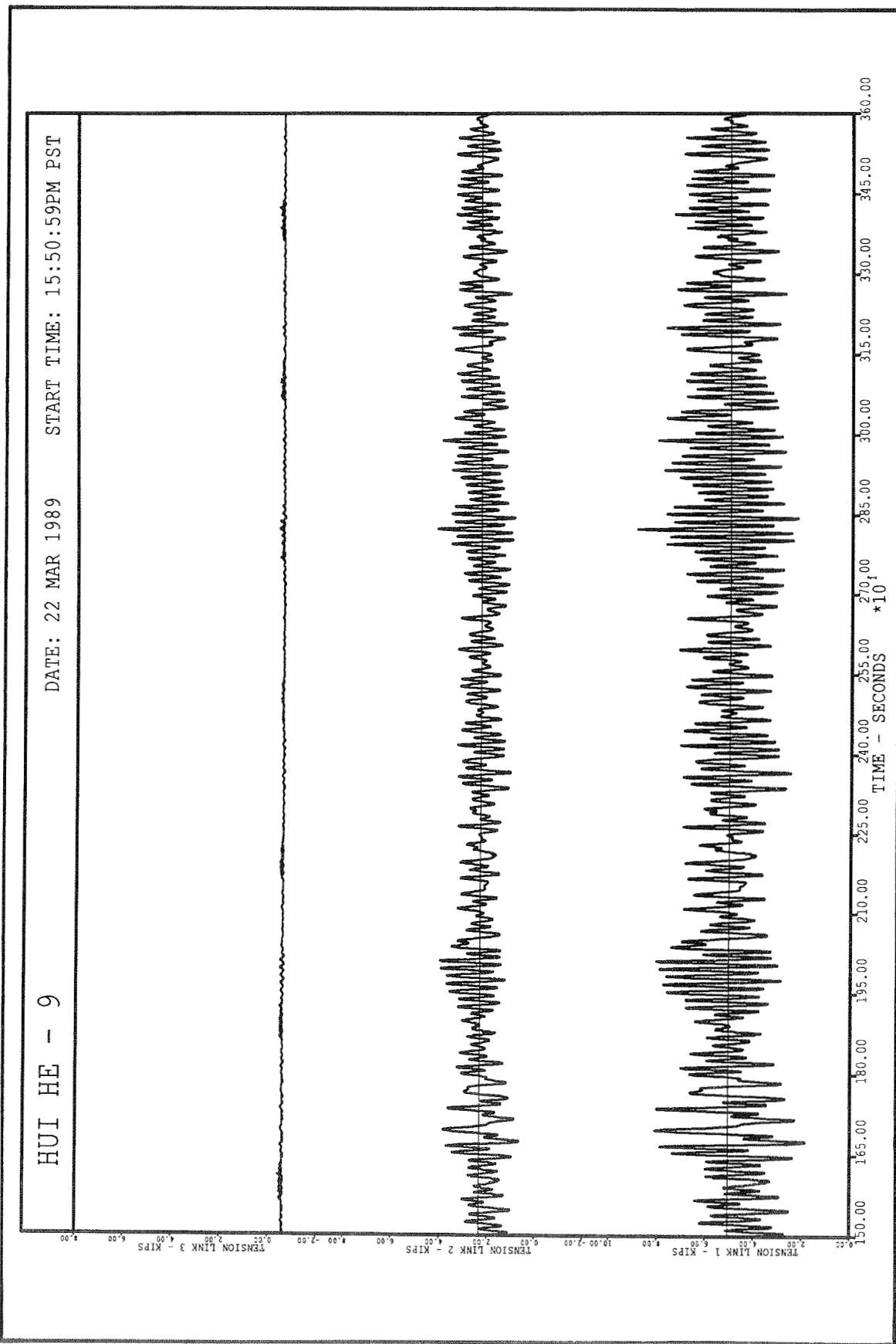
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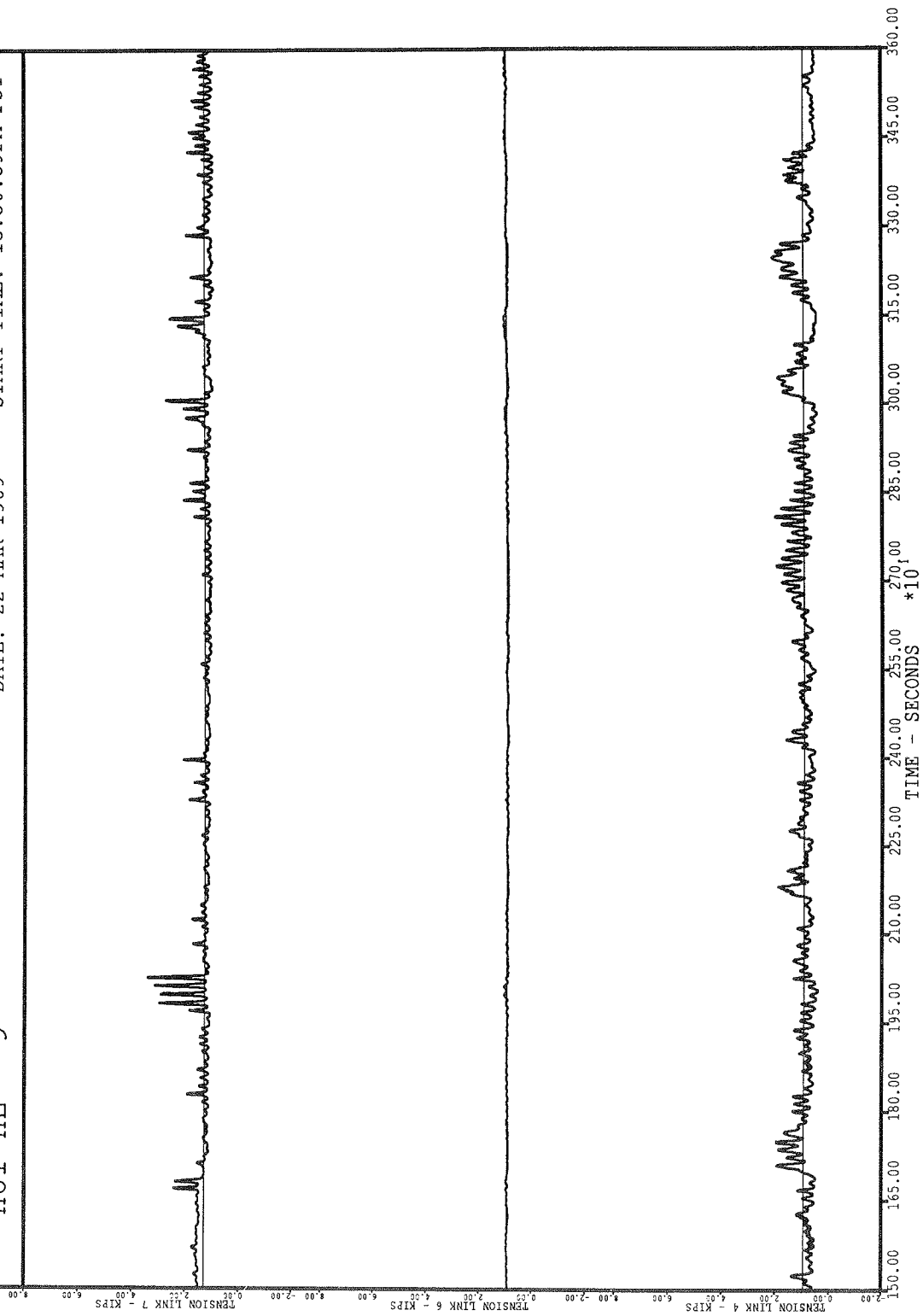


HUI HE - 9 DATE: 22 MAR 1989 START TIME: 15:50:59PM PST





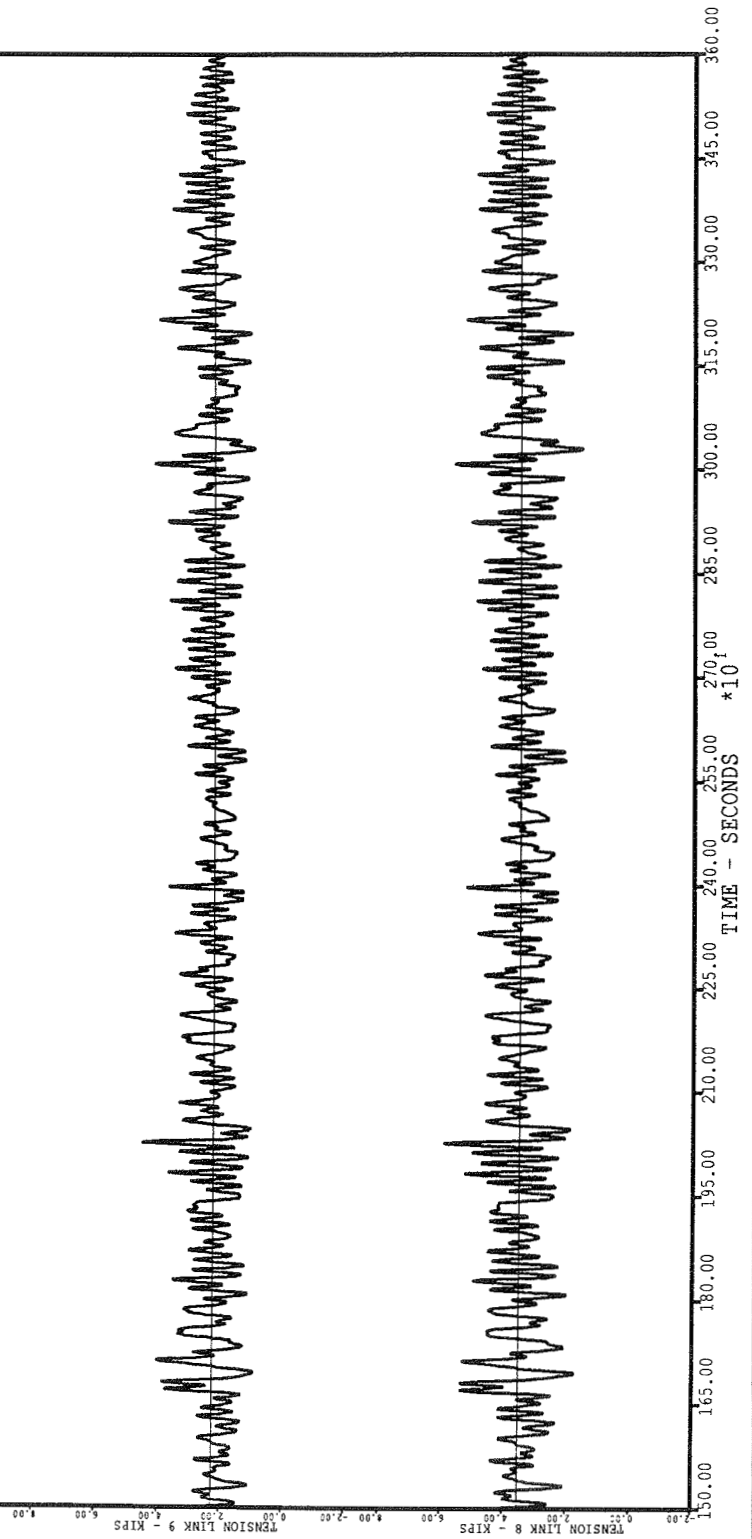
HUI HE - 9 DATE: 22 MAR 1989 START TIME: 15:50:59PM PST



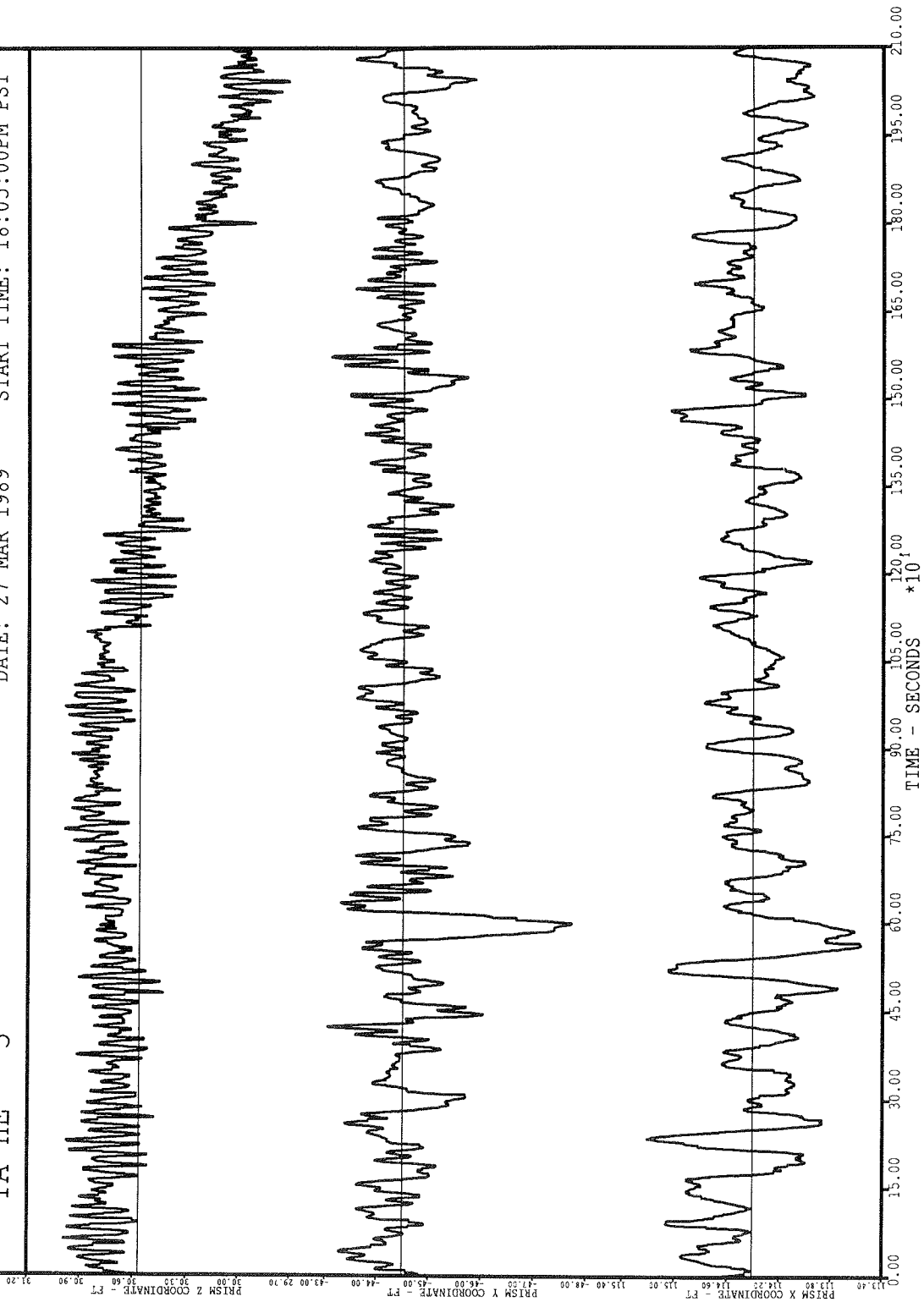
HUI HE - 9

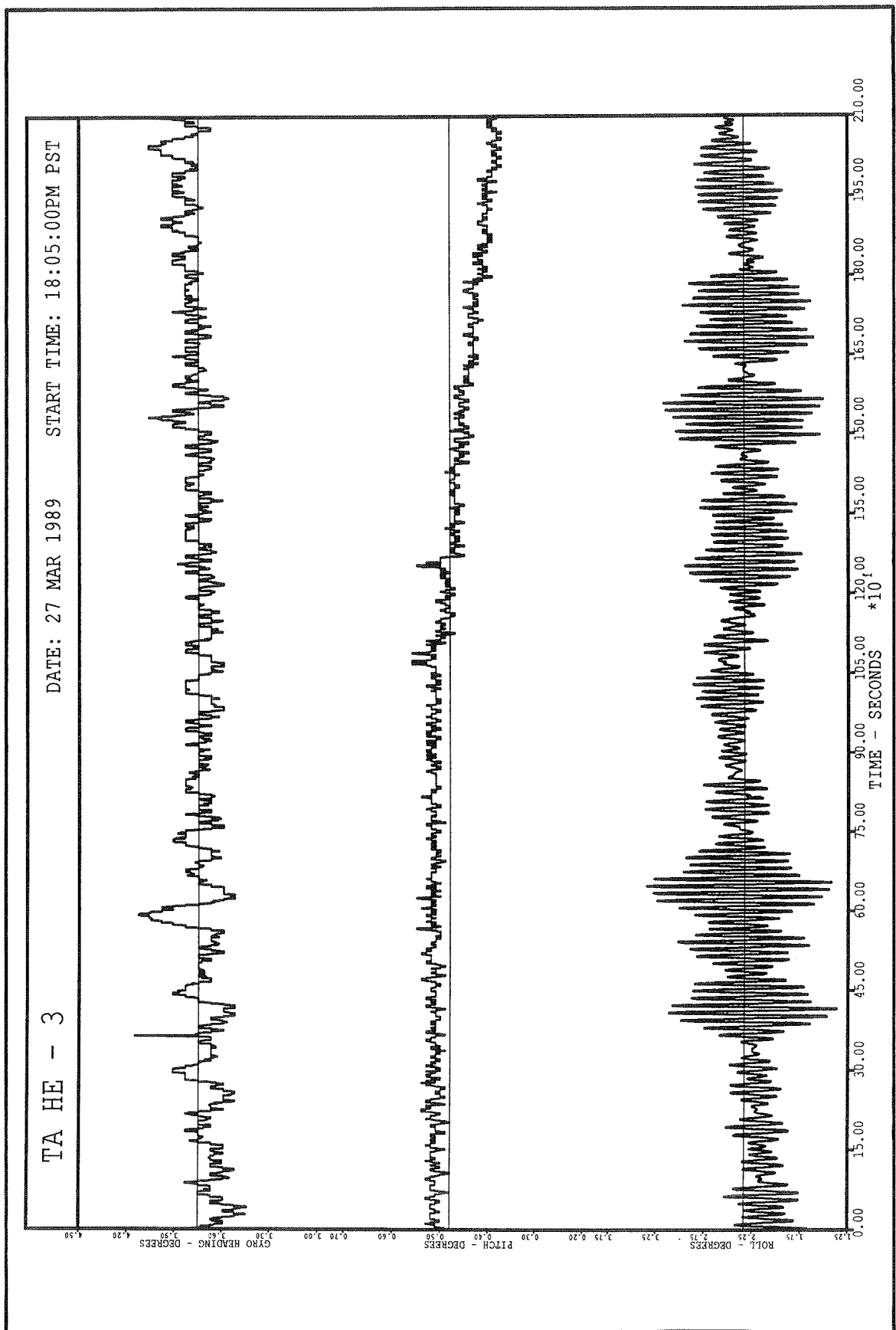
DATE: 22 MAR 1989

START TIME: 15:50:59PM PST



TA HE - 3 DATE: 27 MAR 1989 START TIME: 18:05:00PM PST

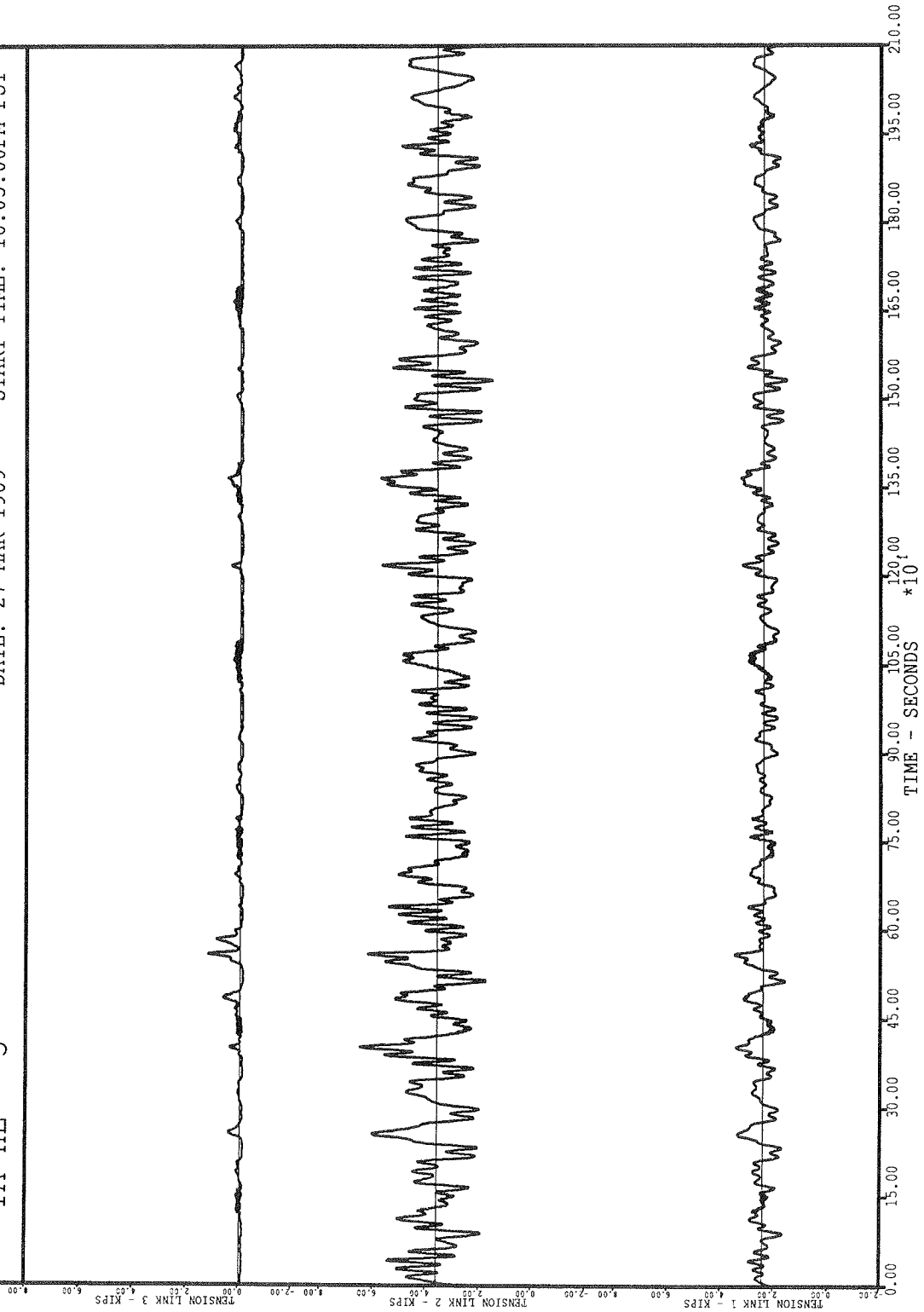


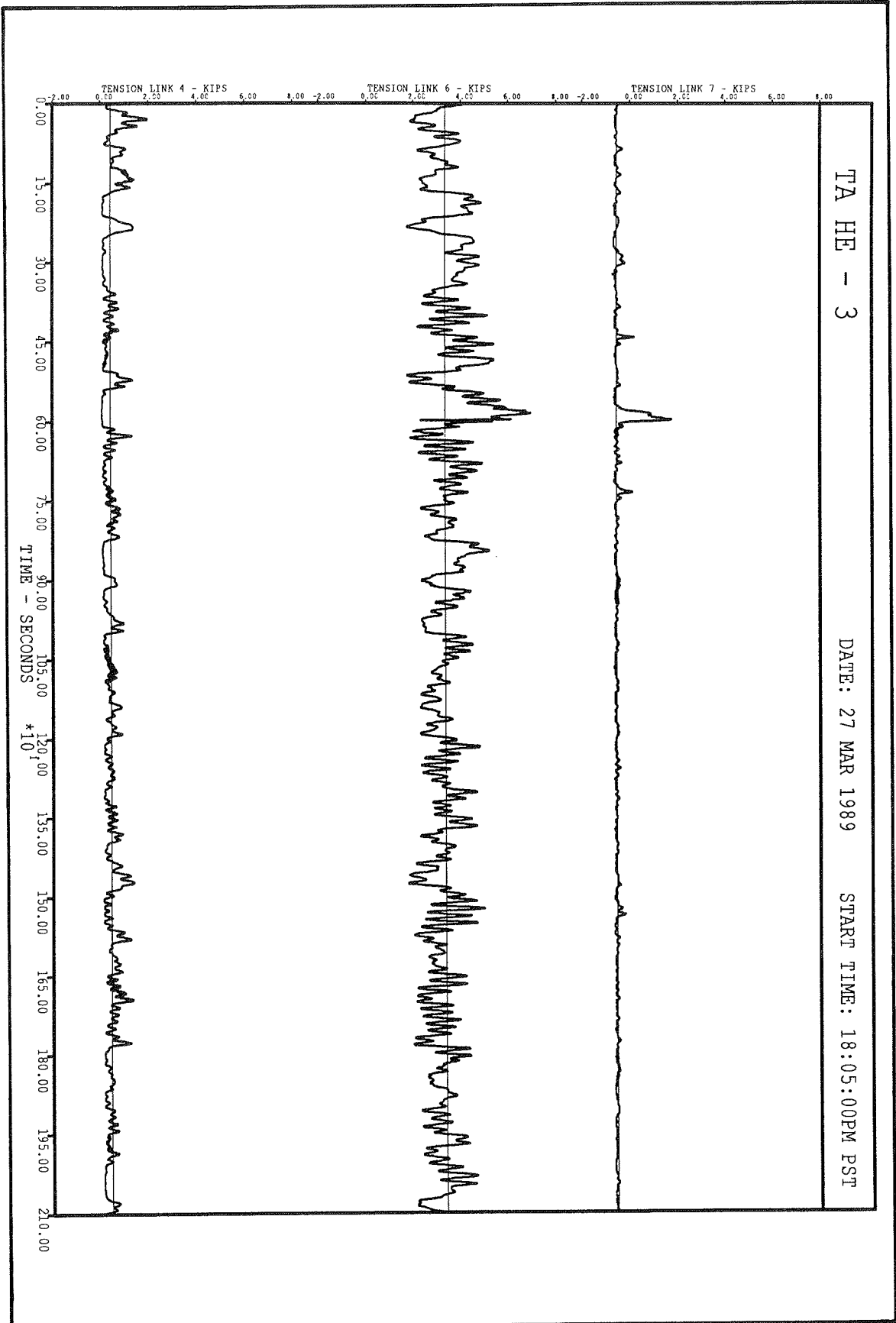


TA HE - 3

DATE: 27 MAR 1989

START TIME: 18:05:00PM PST

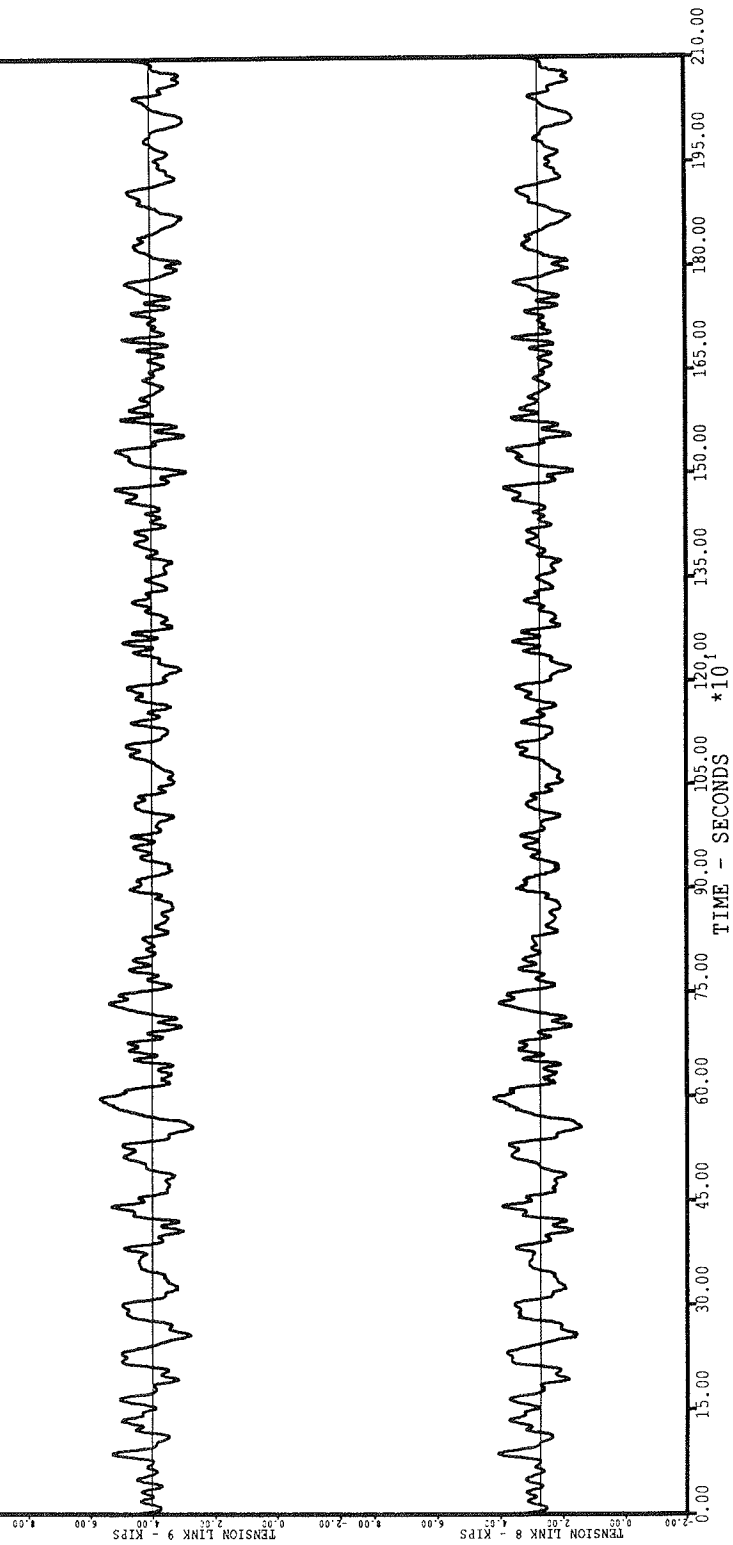


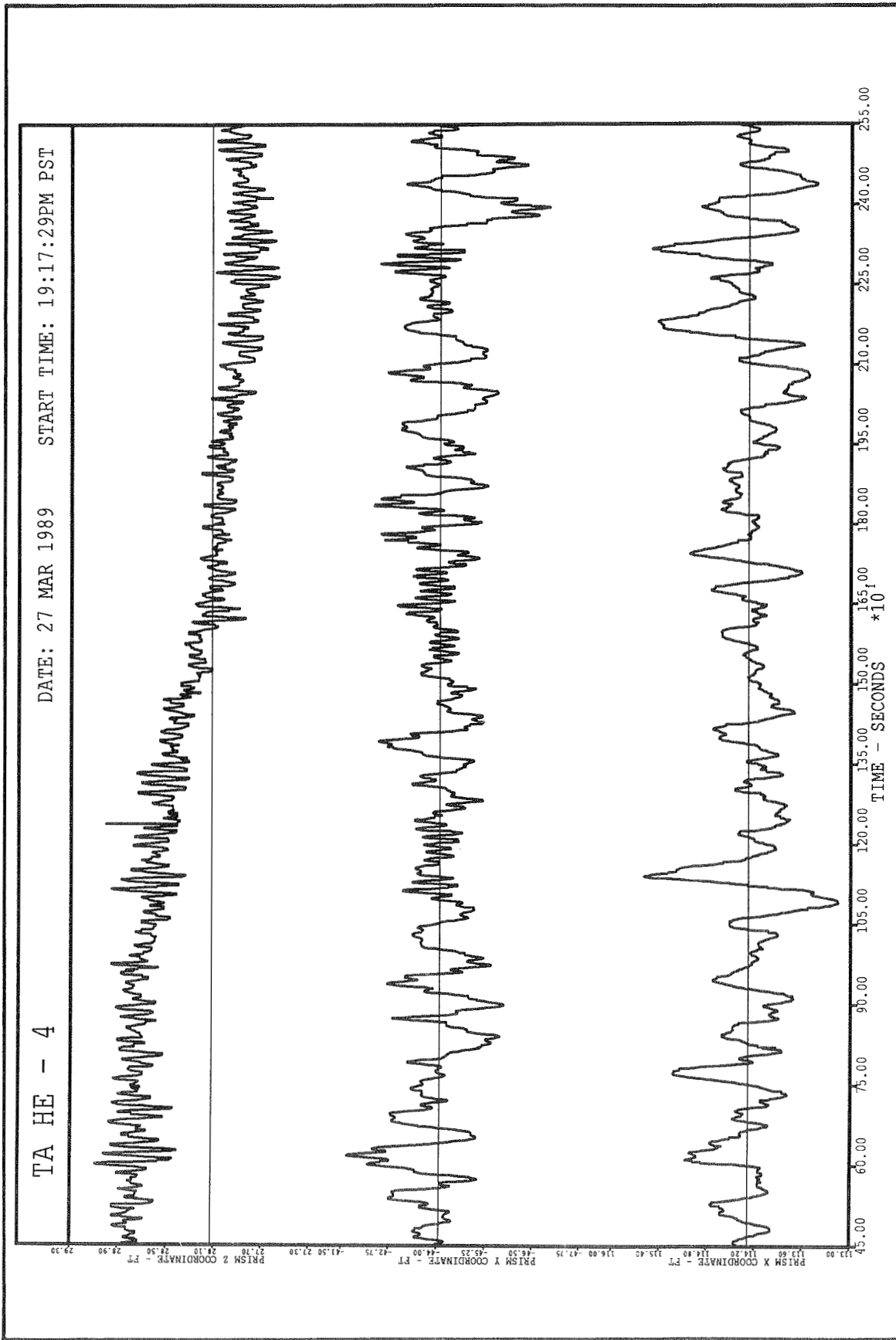


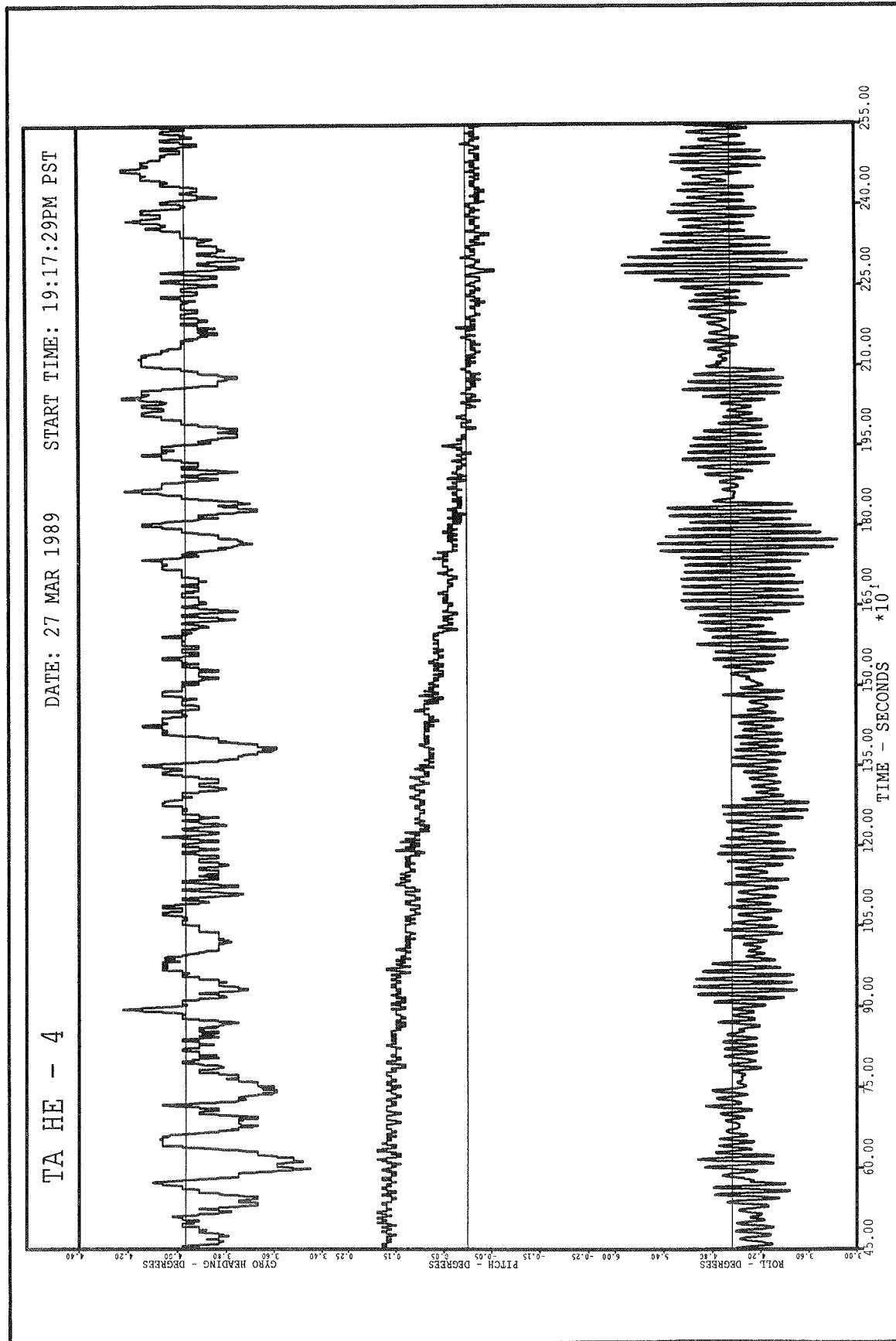
TA HE - 3

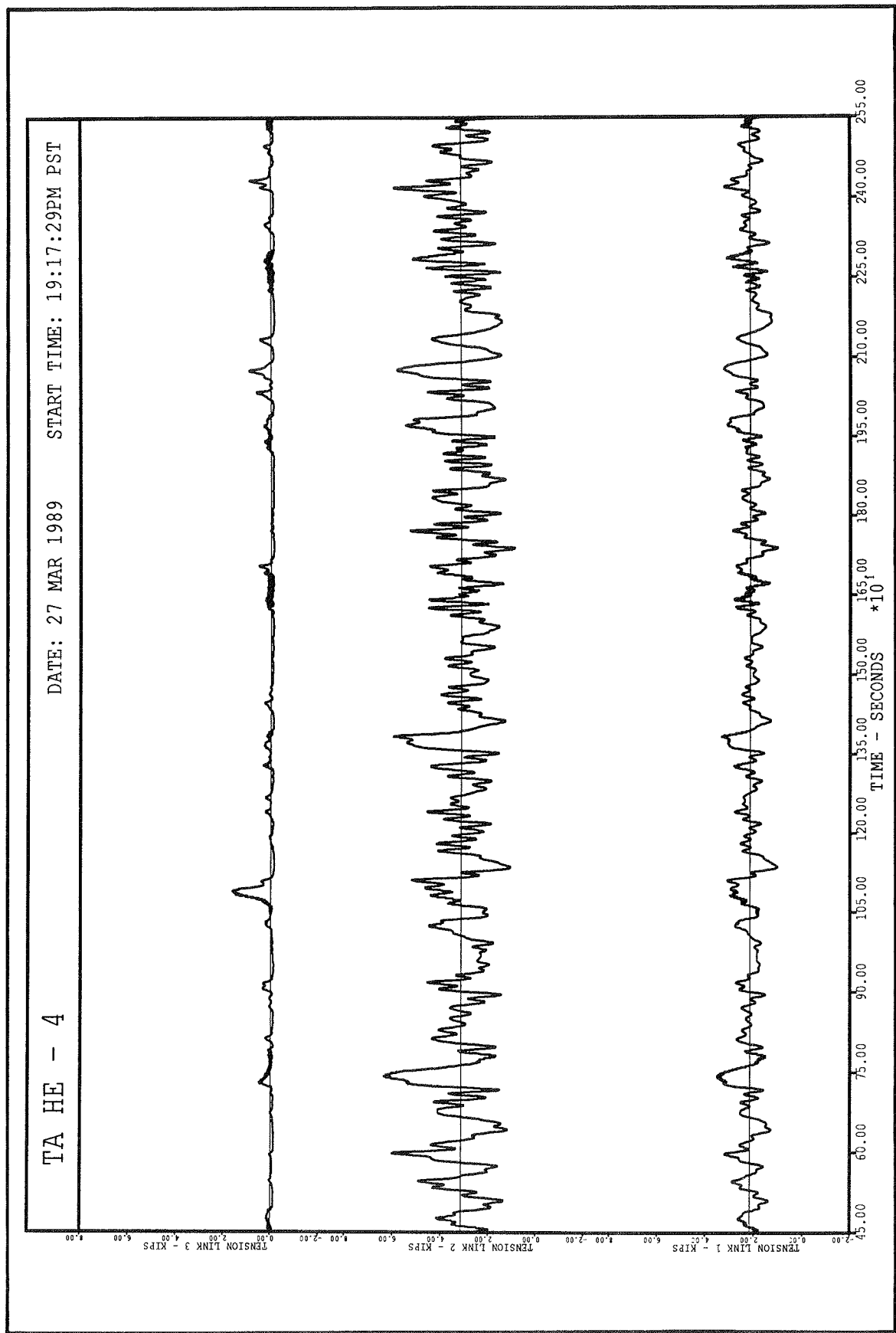
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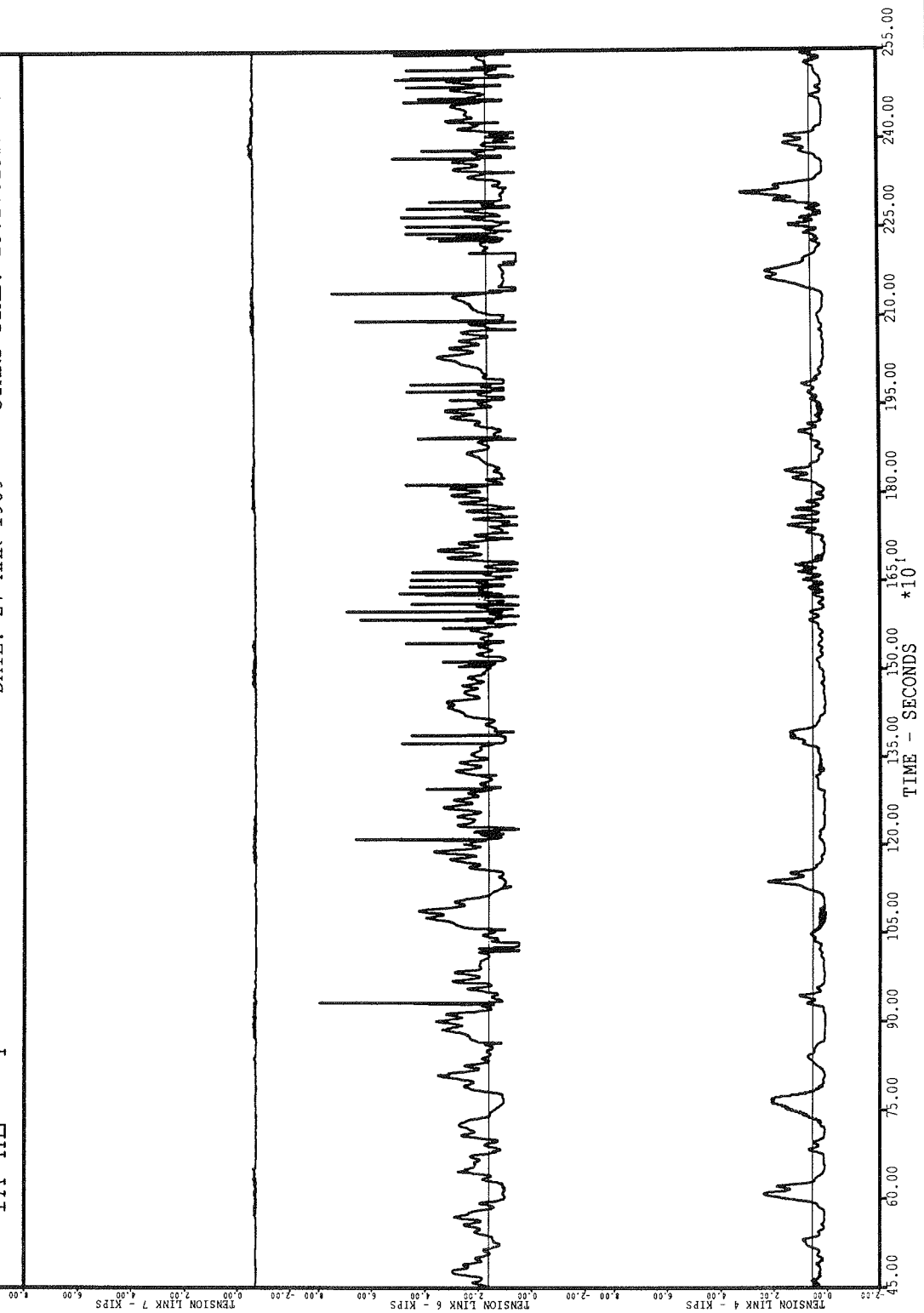








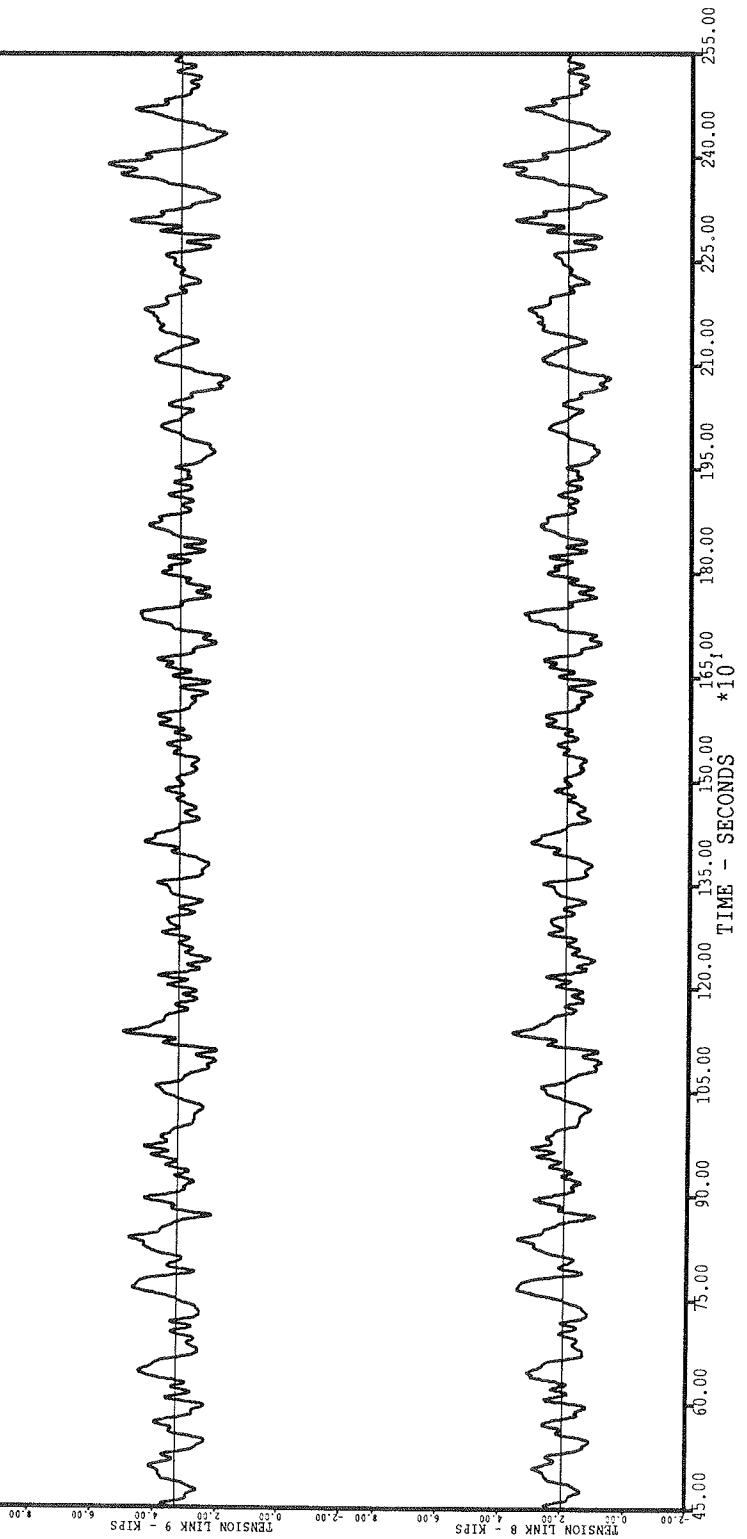
TA HE - 4 DATE: 27 MAR 1989 START TIME: 19:17:29PM PST



TA HE - 4

DATE: 27 MAR 1989

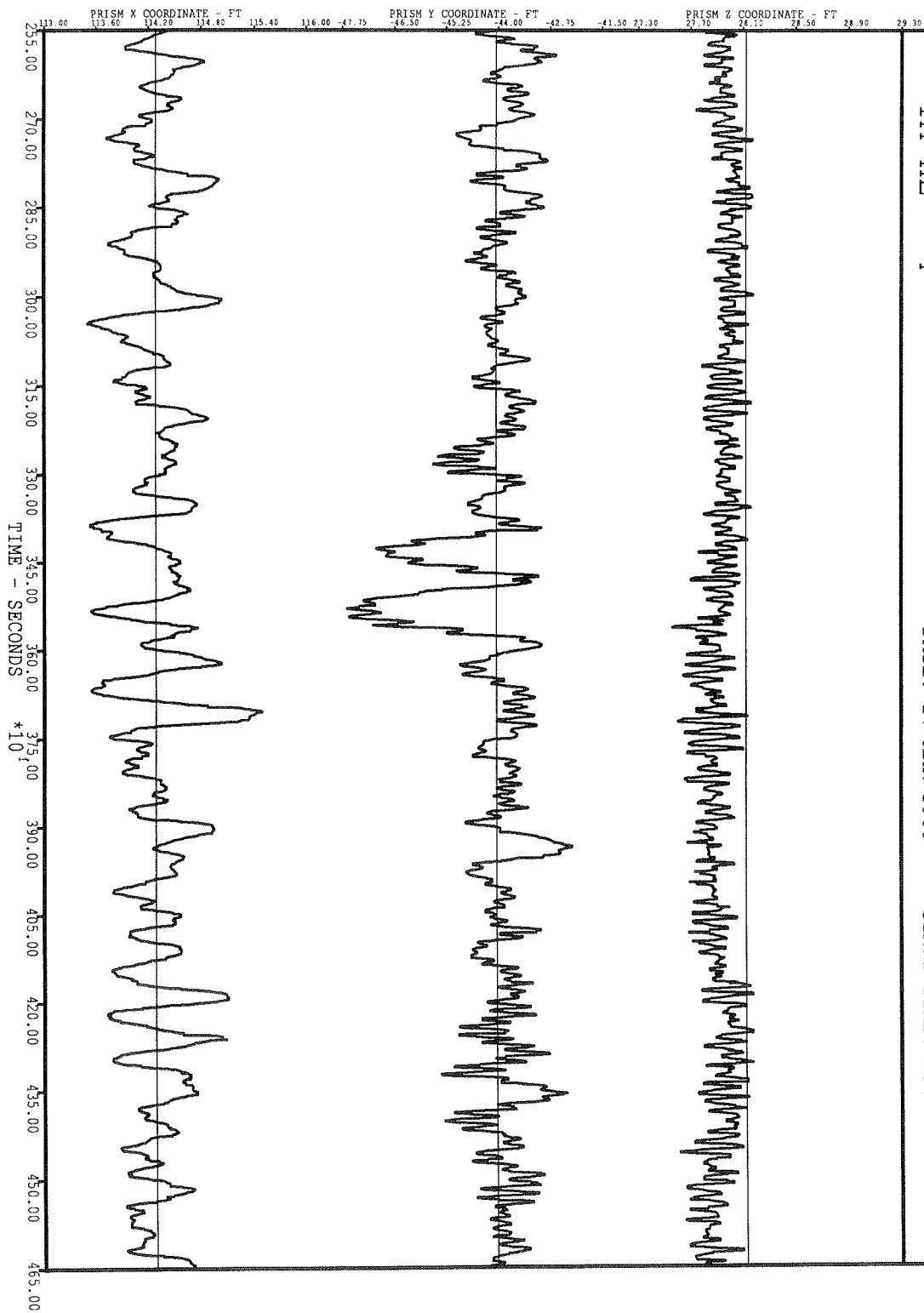
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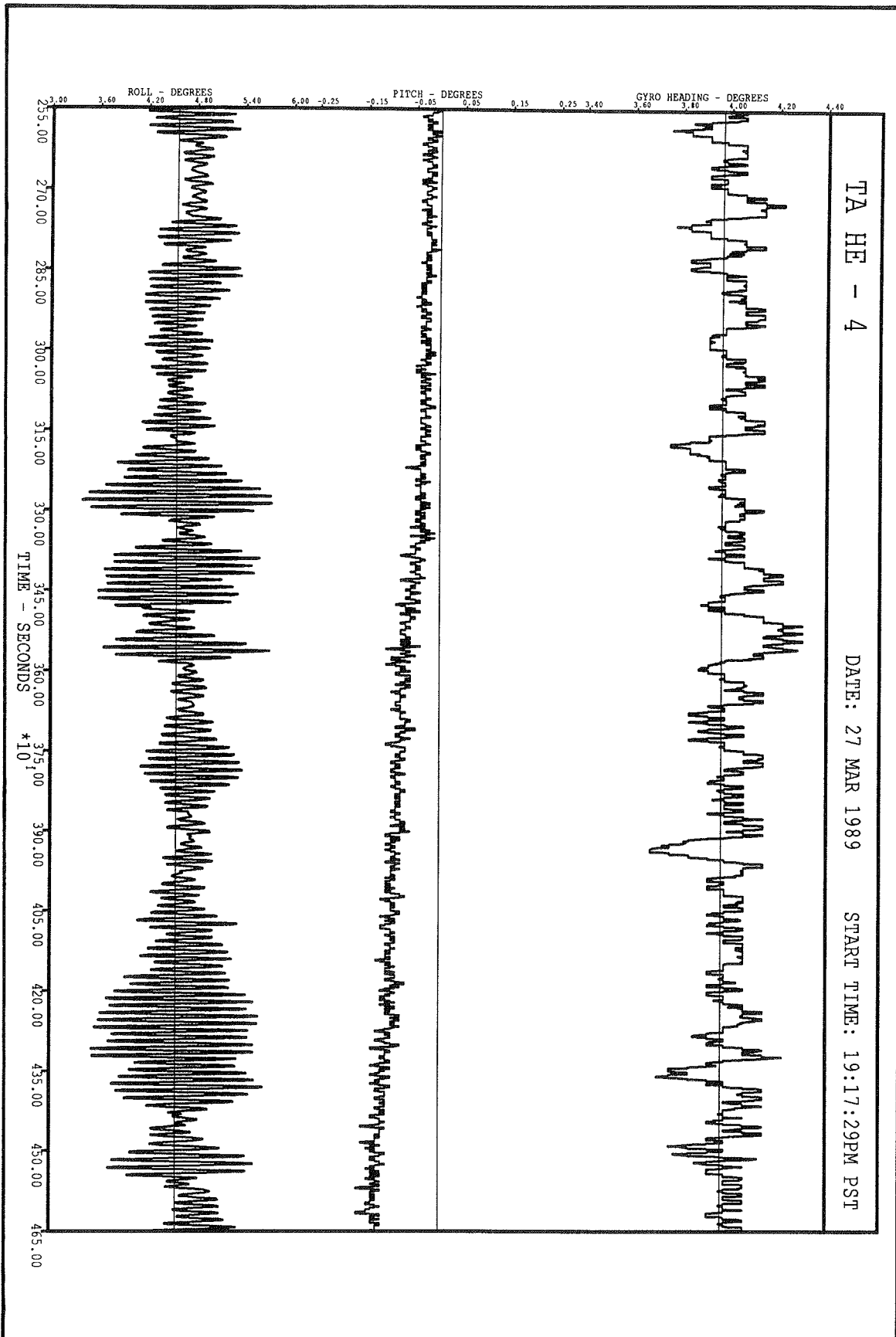


TA HE - 4

DATE: 27 MAR 1989

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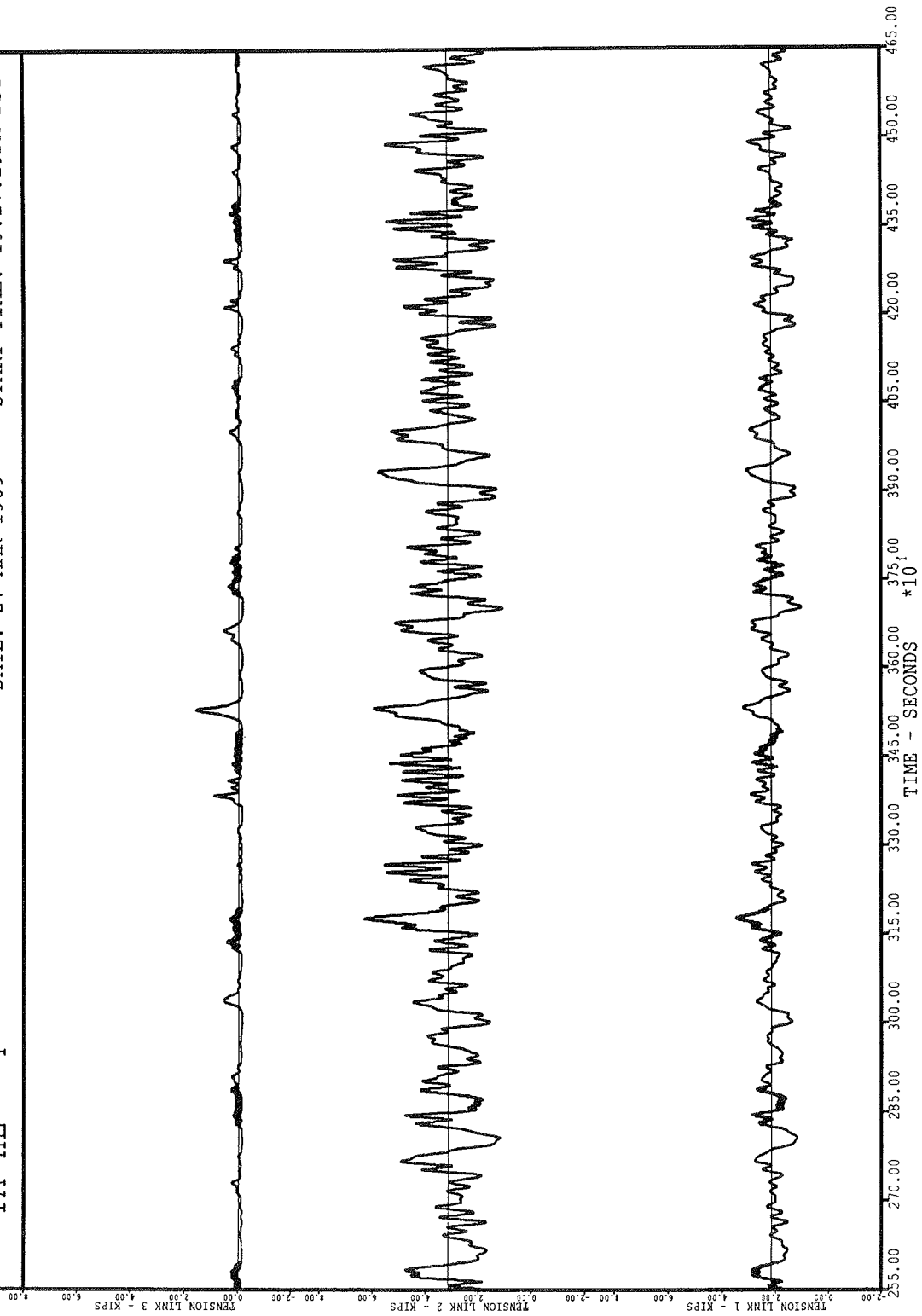




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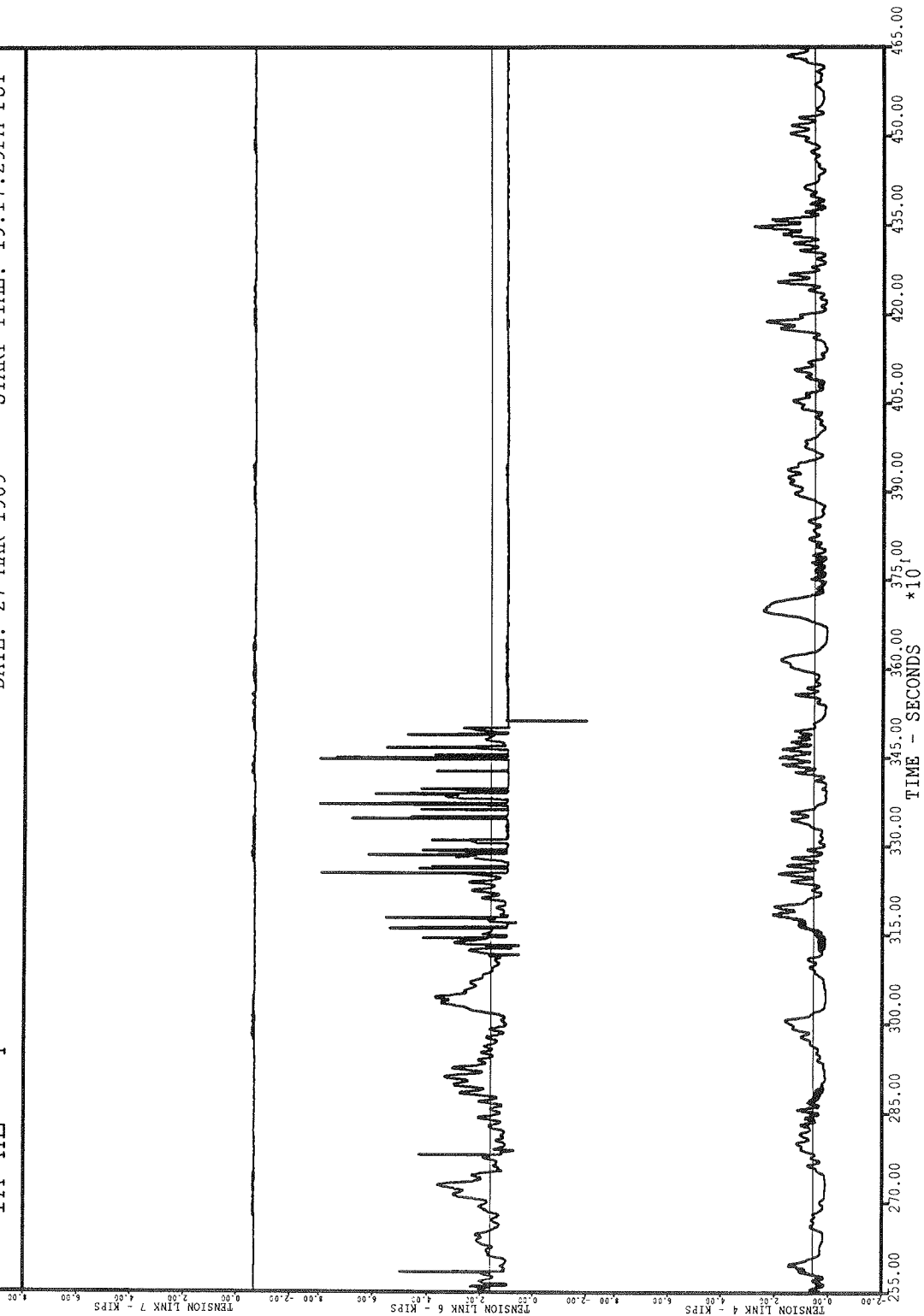
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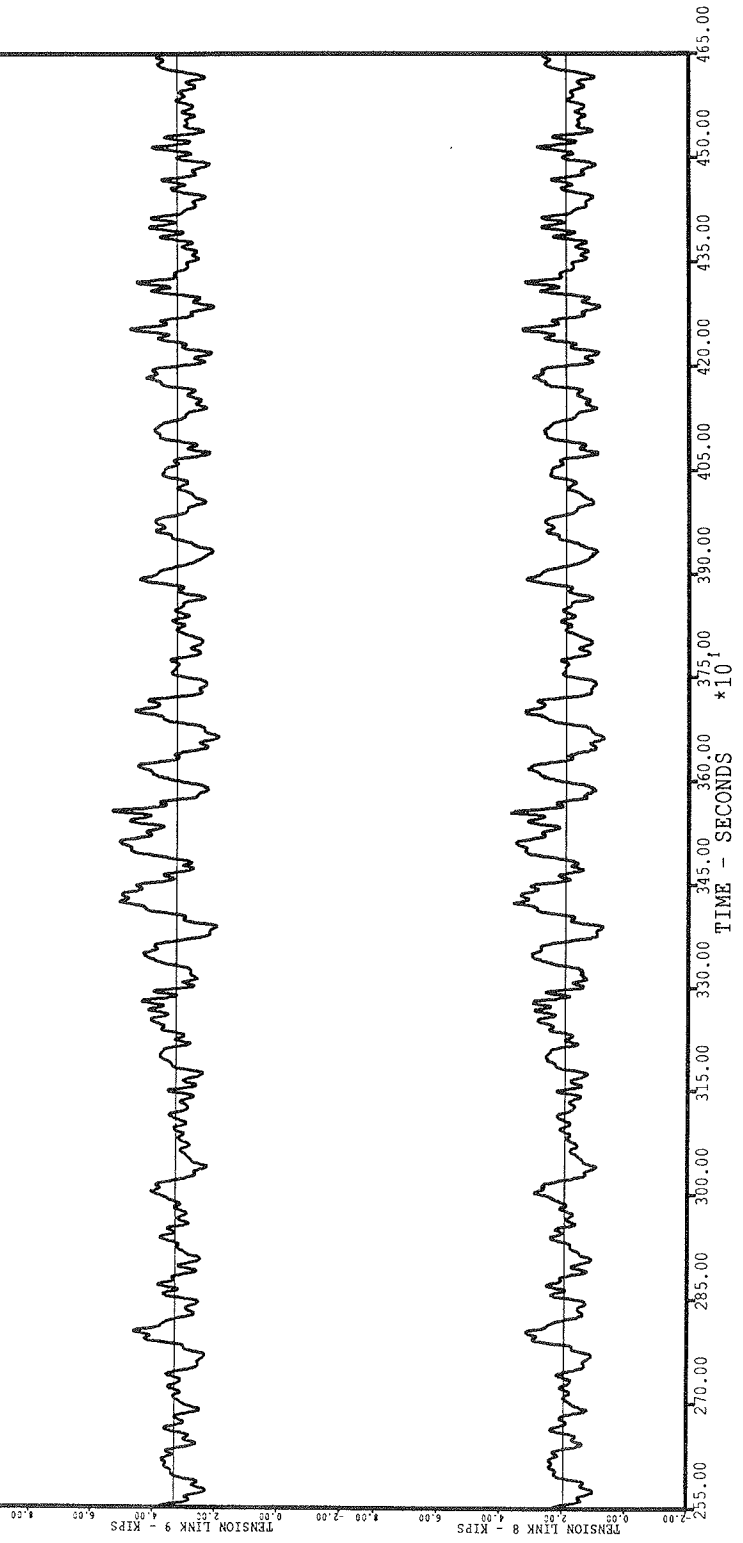
DATE: 27 MAR 1989 START TIME: 19:17:29PM PST

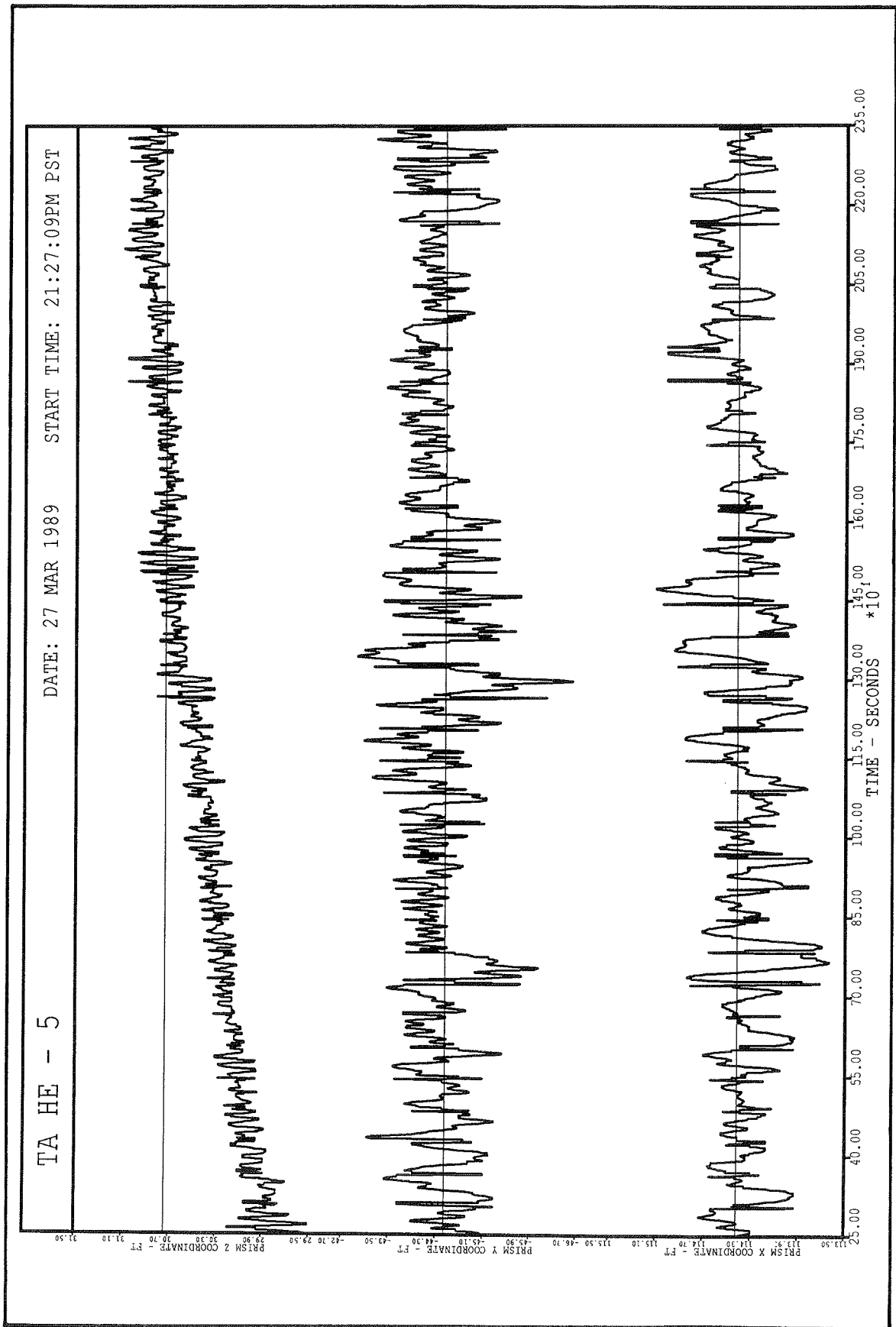


TA HE - 4

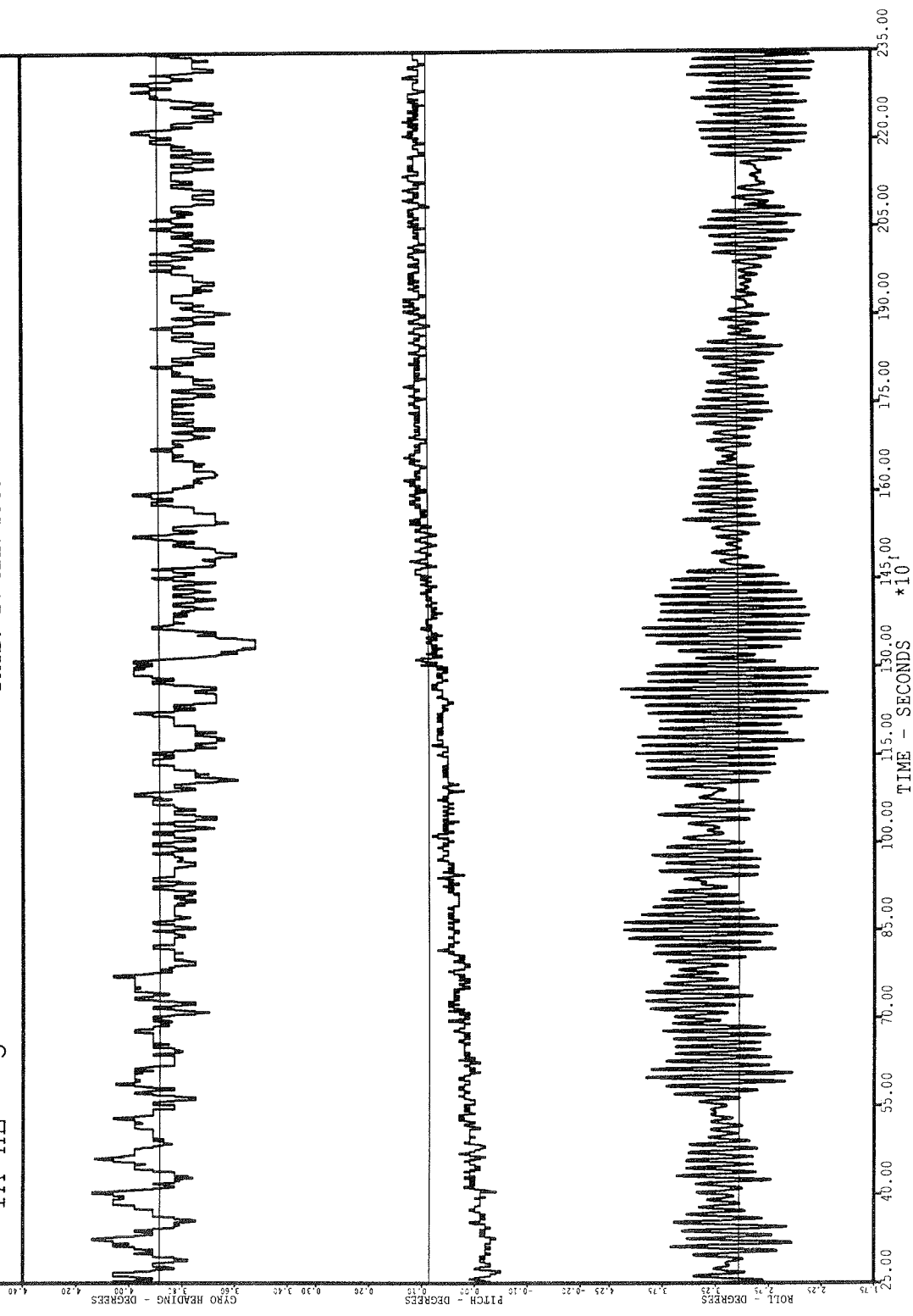
DATE: 27 MAR 1989

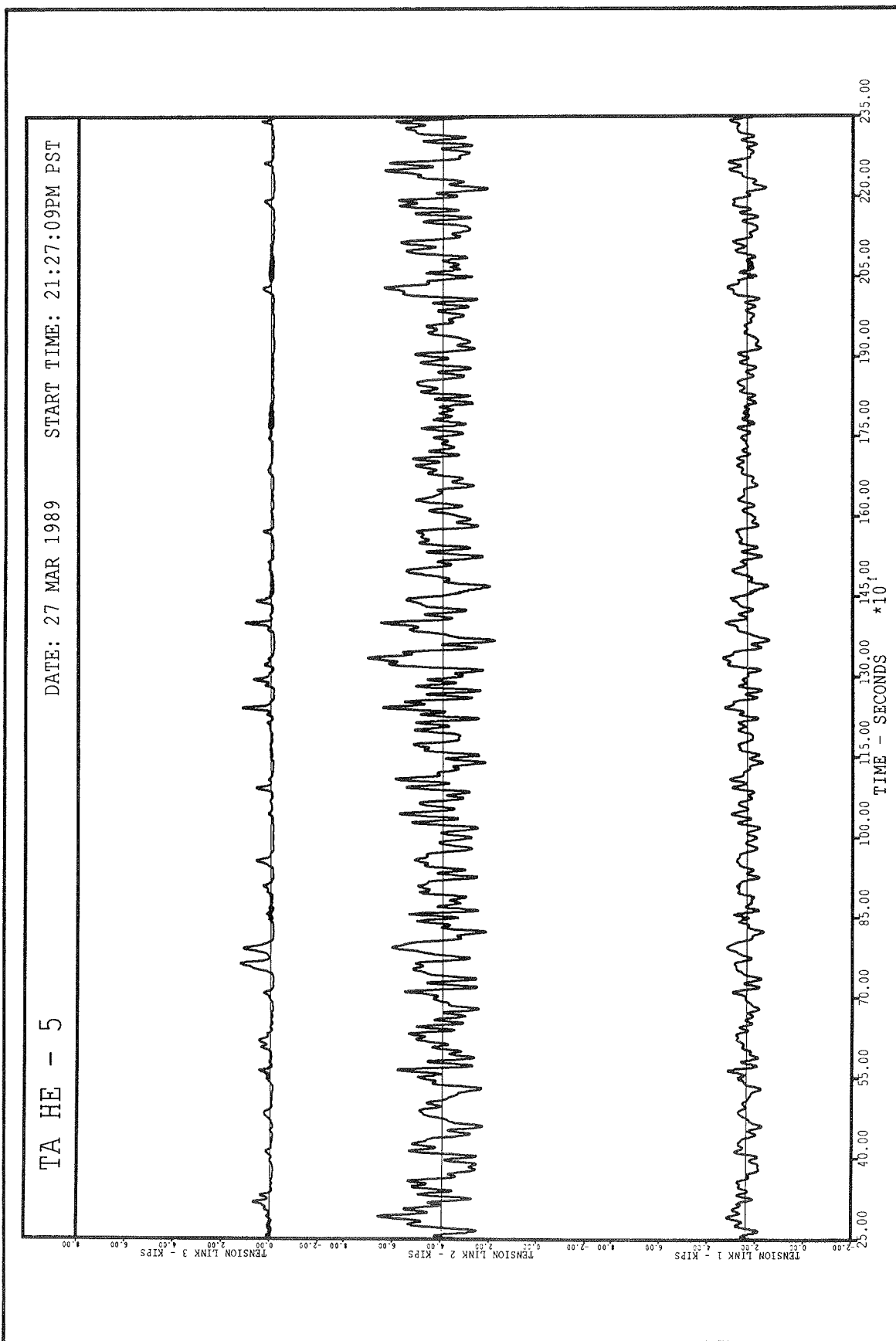
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TA HE - 5 DATE: 27 MAR 1989 START TIME: 21:27:09PM PST

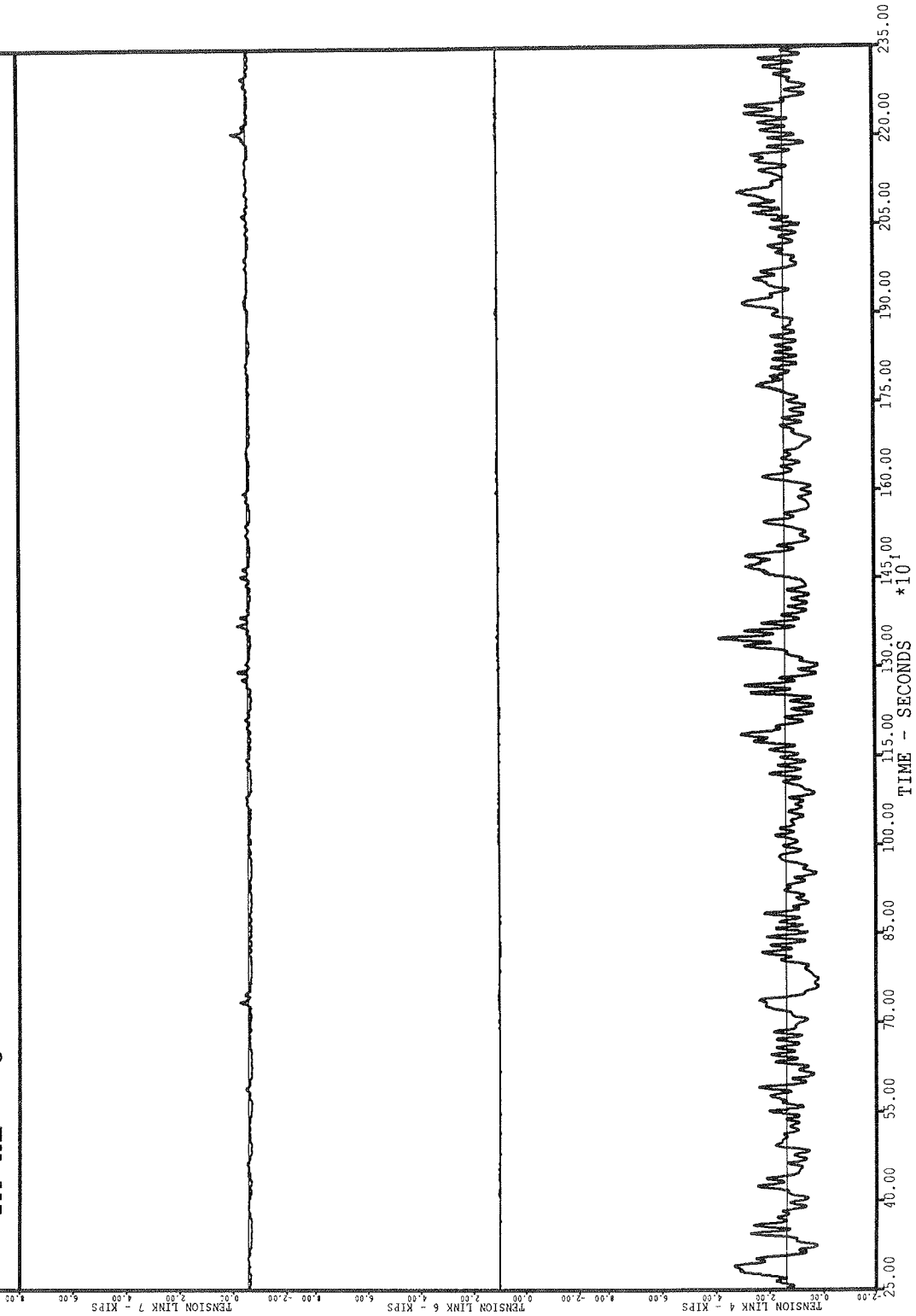




TA HE - 5

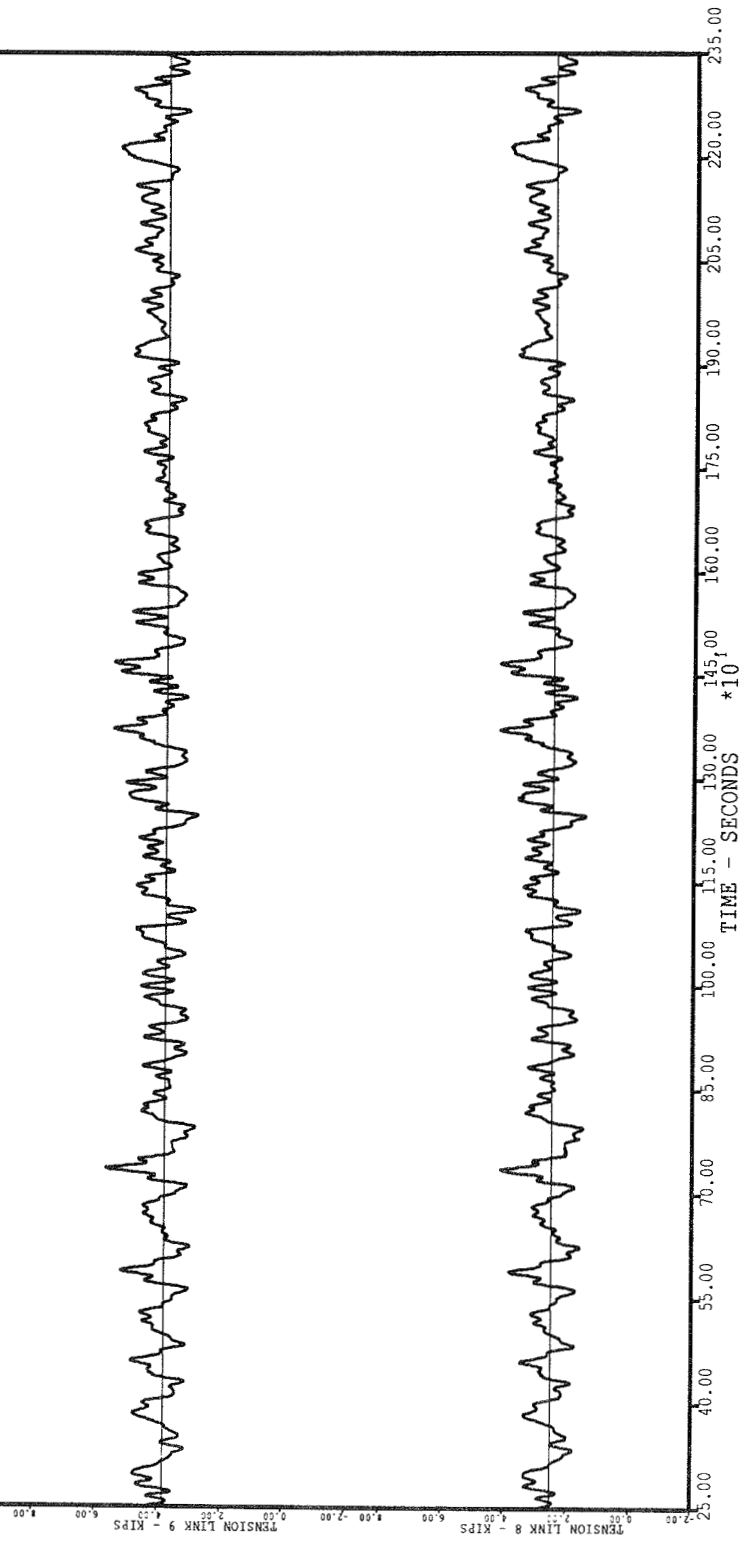
DATE: 27 MAR 1989

START TIME: 21:27:09PM PST

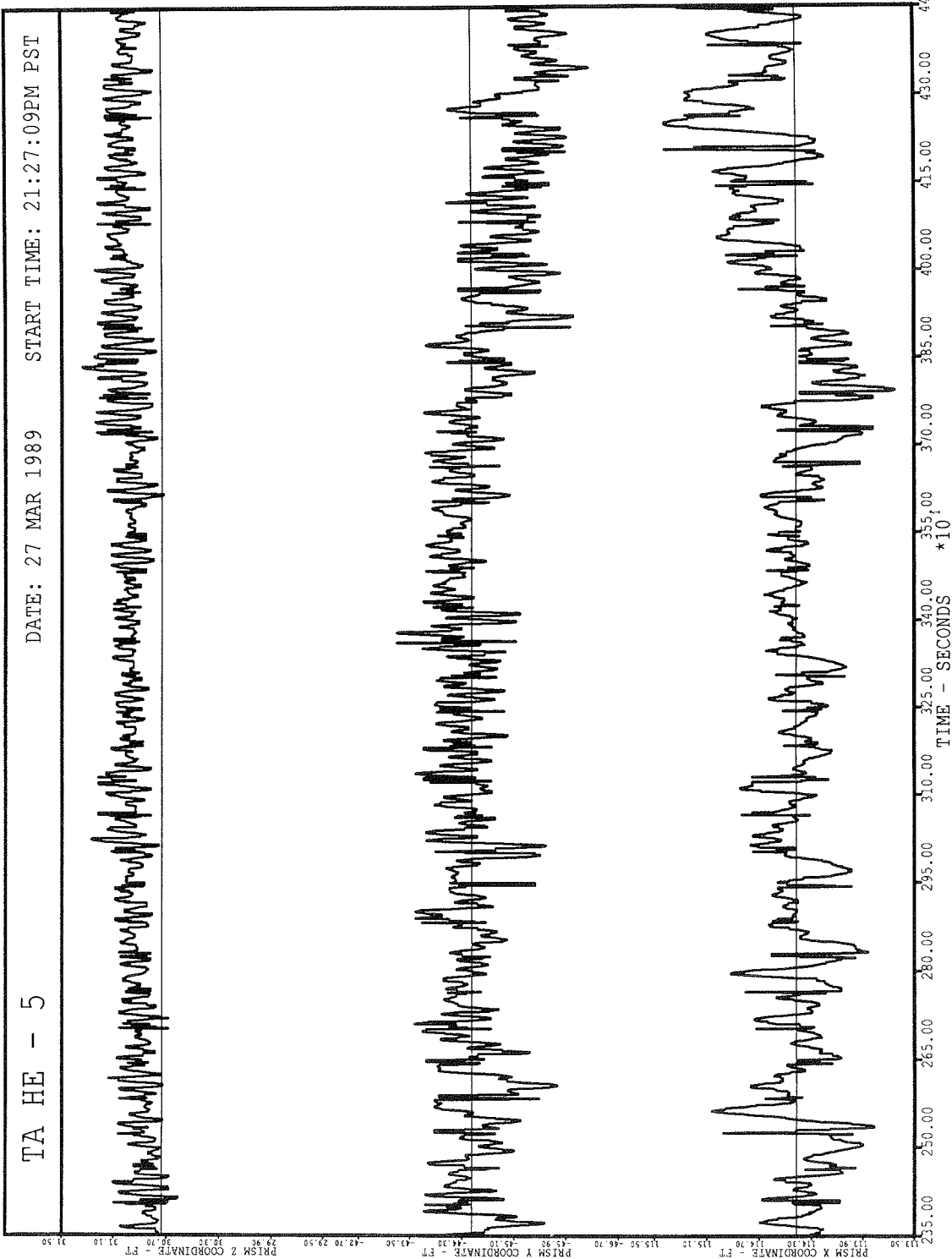


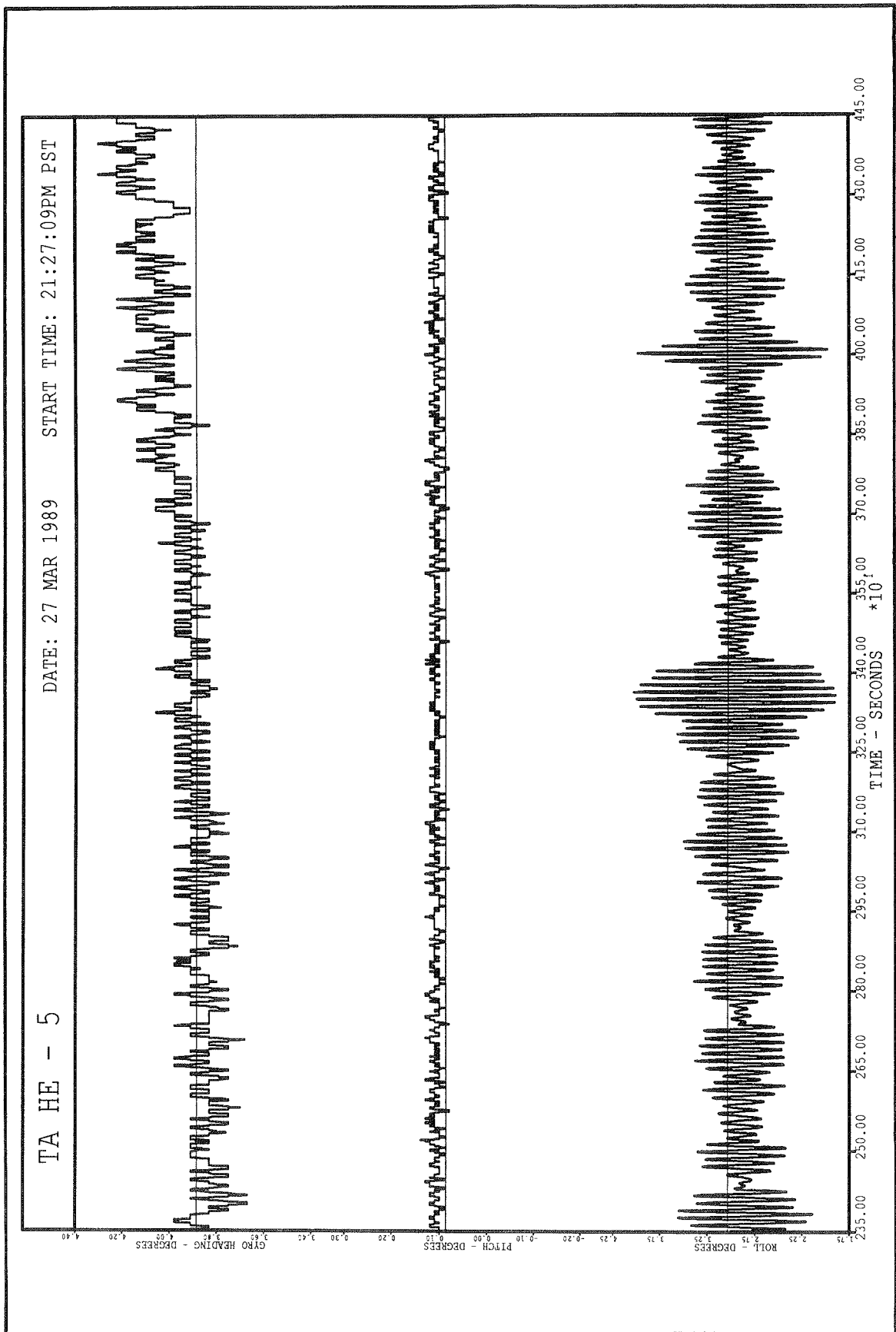
TA HE - 5

DATE: 27 MAR 1989 START TIME: 21:27:09PM PST



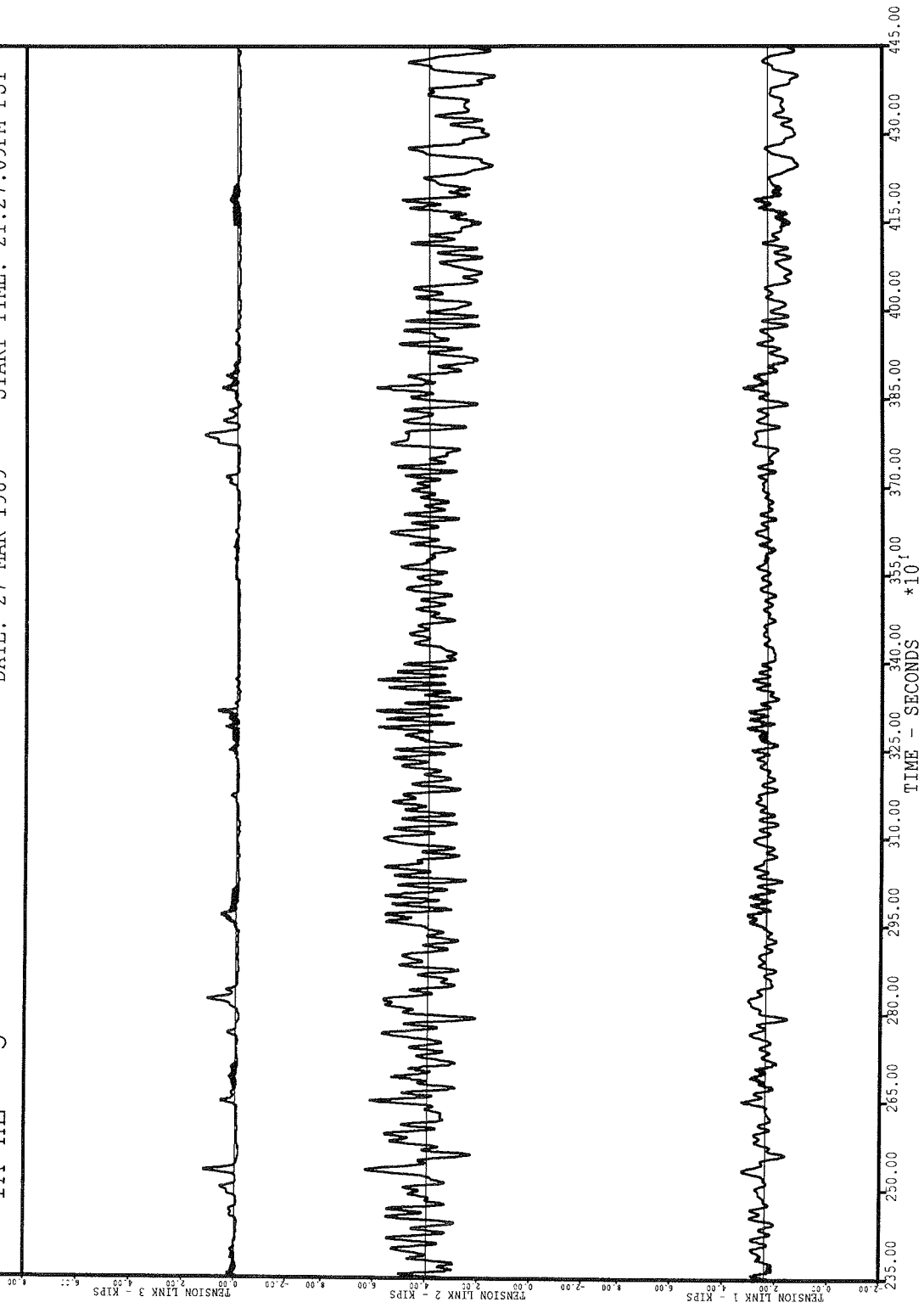
TA HE - 5 DATE: 27 MAR 1989 START TIME: 21:27:09PM PST

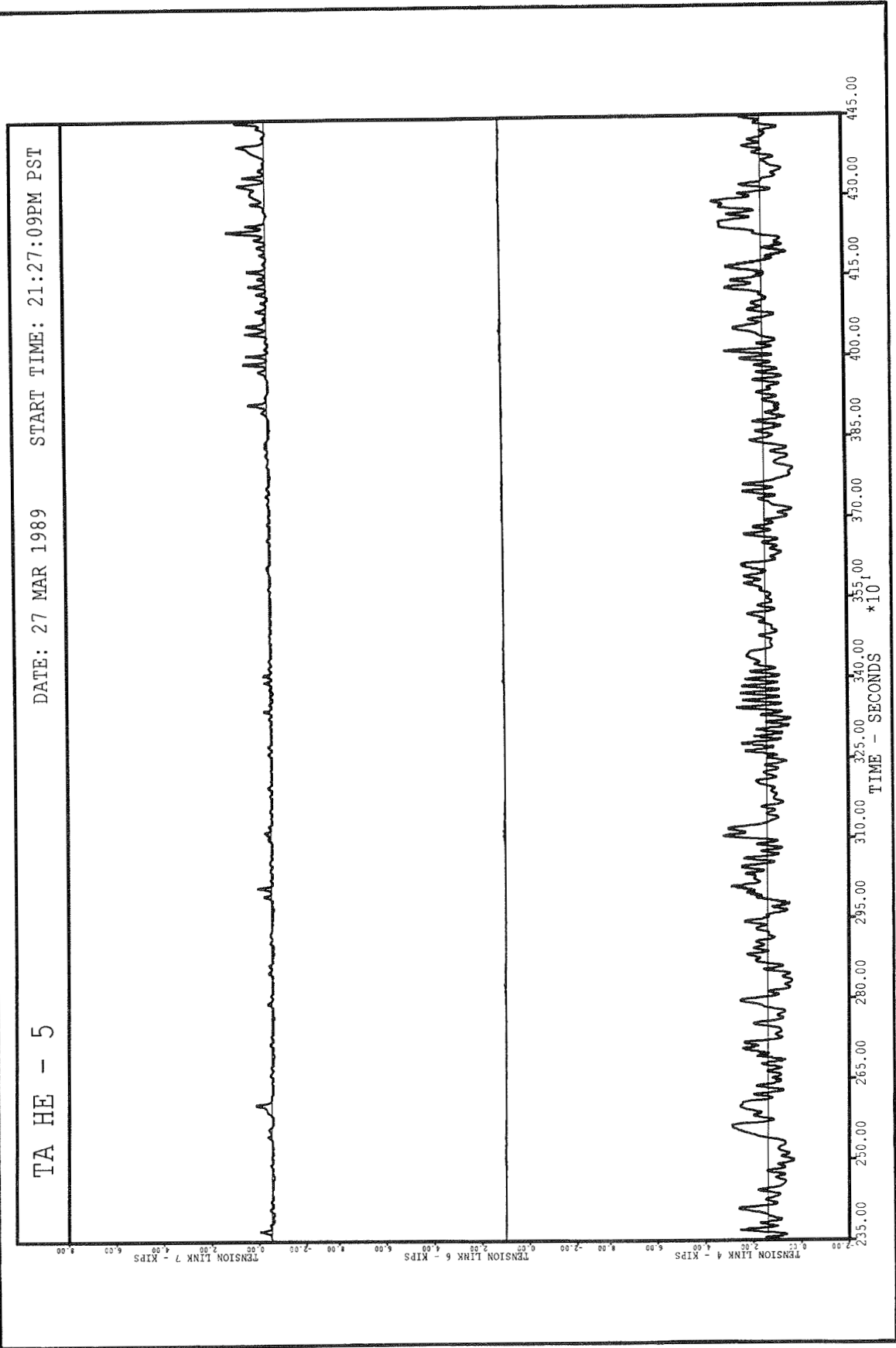




TA HE - 5

DATE: 27 MAR 1989 START TIME: 21:27:09PM PST





TA HE - 5 DATE: 27 MAR 1989 START TIME: 21:27:09PM PST

